GEOSYNTHETIC REINFORCEMENT
OF THE
AGGREGATE BASE/SUBBASE COURSES
OF
PAVEMENT STRUCTURES

GMA WHITE PAPER II

Prepared for:
AASHTO Committee 4E

Prepared by:
Geosynthetic Materials Association

June 27, 2000

<table>
<tr><td>1. REPORT NO.</td><td>2.</td><td colspan="2">3. RECIPIENT'S CATALOG NO.</td></tr>
<tr><td colspan="2" rowspan="2">4. TITLE AND SUBTITLE

Geosynthetic Reinforcement of the Aggregate Base/Subbase Courses of Pavement Structures</td><td colspan="2">5. REPORT DATE
June 2000</td></tr>
<tr><td colspan="2">6. PERFORMING ORGANIZATION CODE</td></tr>
<tr><td colspan="2">7. AUTHOR(S)

Ryan R. Berg, P.E.; Barry R. Christopher, P.E., Ph.D.; and Steven Perkins, P.E., Ph.D.</td><td colspan="2">8. PERFORMING ORGANIZATION REPORT NO.</td></tr>
<tr><td colspan="2" rowspan="2">9. PERFORMING ORGANIZATION NAME AND ADDRESS

Ryan R. Berg & Associates, Inc.
2190 Leyland Alcove
Woodbury, MN 55125</td><td colspan="2">10. WORK UNIT NO.</td></tr>
<tr><td colspan="2">11. CONTRACT OR GRANT NO.</td></tr>
<tr><td colspan="2" rowspan="2">12. SPONSORING AGENCY NAME AND ADDRESS

Geosynthetic Materials Association
1801 County Road B West
Roseville, MN 55113</td><td colspan="2">13. TYPE OF REPORT AND PERIOD COVERED</td></tr>
<tr><td colspan="2">14. SPONSORING AGENCY CODE</td></tr>
<tr><td colspan="4">15. SUPPLEMENTARY NOTES

Technical Consultant: Joel Sprague, P.E.</td></tr>
<tr><td colspan="4">16. ABSTRACT
Geosynthetic reinforcement of the base, or subbase, course of pavement structures is addressed. The value added with reinforcement, design criteria/protocols, and practices for design and for material specifications are presented. Base, or subbase, reinforcement is defined within as the use of geosynthetic reinforcement in flexible pavements to support vehicular traffic over the life of a pavement structure. Primary base reinforcement benefits are to improve the service life and/or obtain equivalent performance with a reduced structural section. Substantial life-cycle cost savings are possible with base reinforcement. Cost saving benefits should be quantified using life-cycle analyses, and on an agency specific basis due to the many input variables. Recommended design procedure and material specifications are presented. It is recommended that specification with an approved products list be utilized, as the mechanisms of reinforcement are not fully understood and the geosynthetic performance should be considered product, and test conditions, specific. Equivalent materials must demonstrate equivalent performance in test structures and/or possess equivalent material properties, as defined by the specifier.
The use of geosynthetic reinforcement to aid in construction over low strength subgrades, termed subgrade restraint within, is also addressed. Geosynthetic reinforcement is used to increase the support equipment during construction of a roadway. Subgrade restraint design procedures are based upon either (i) generic material properties, wherein a generic specification can be prepared based upon those design property requirements; or (ii) product-specific, empirically derived design methods, wherein an approved products list specification approach may be used.
Geogrid, geotextile, and geogrid-geotextile composite materials are addressed within.
This paper provides government agencies with current, logical recommended practice for the systematic use of geosynthetic reinforcement of pavement base courses. Refined guidance should be developed as the use of base reinforcement increases and additional long-term performance data becomes available.</td></tr>
<tr><td colspan="2">17. KEY WORDS

roadway design, reinforcement, geosynthetics, geogrids, geotextiles, geocomposites, base reinforcement, subgrade restraint, lateral restraint, separation, life-cycle costs, design procedures, specifications</td><td colspan="2">18. DISTRIBUTION STATEMENT

No restrictions.</td></tr>
<tr><td>19.</td><td>20.</td><td>21. NO. OF PAGES

176</td><td>22.</td></tr>
</table>

SI CONVERSION FACTORS				
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	millimeters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
		TEMPERATURE		
°C	Celsius	1.8 C + 32	Fahrenheit	°F
		WEIGHT DENSITY		
kN/m^3	kilonewton / cubic meter	6.36	poundforce / cubic foot	pcf
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kN	kilonewtons	225	poundforce	lbf
kPa	kilopascals	0.145	poundforce / square inch	psi
kPa	kilopascals	20.9	poundforce / square foot	psf

Preface

The opinions stated within this paper are solely those of the authors, except as noted otherwise, and do not necessarily represent the views or opinions of the financial sponsors of this work. The scope of this paper is summarized in the Introduction. Financial sponsorship was provided by the Geosynthetic Materials Association (GMA) technical committee, and by the following GMA members: Amoco Fabrics & Fibers Co.; Colbond Geosynthetics; Contech Construction Products, Inc.; Huesker, Inc.; Maccaferri Gabions, Inc.; Synthetic Industries; TC Mirafi; Tenax Corporation; Tensar Earth Technologies; and TNS Advanced Technologies.

Signature Page

EXECUTIVE SUMMARY

This *White Paper* has been prepared to support the efforts of the AASHTO 4E Task Group in its efforts to develop specifications for geosynthetic reinforcement of the aggregate base course of pavement structures. The goal for this second Geosynthetic Materials Association (GMA) white paper is to document the value added to pavement structures when geosynthetics are used to reinforce the aggregate base. Specific objectives associated with this goal are to document the following:

- Value added to pavements in reinforcement of pavement structure;
- Design criteria/protocol(s); and
- Practices for design and material specification.

Base reinforcement results from the addition of a geosynthetic at the bottom or within a base course to increase the structural or load-carrying capacity of a pavement system by the transfer of load to the geosynthetic material. The two main benefits of the reinforcement are to (1) improve the service life and/or; (2) obtain equivalent performance with a reduced structural section. Base reinforcement could also be thought to provide a safety factor on the pavement load-carrying capacity against significantly increased EASLs, or weaker subgrade from design values or inaccuracies in the pavement design methodology. The primary mechanism associated with this application is lateral restraint or confinement. Based on a literature review (see Section 2) of research from or directly pertinent to North American pavement practices, many benefits can be derived from reinforcement of paved, permanent pavements with geosynthetics, as discussed in Section 3.

Substantial life-cycle cost savings are possible with geosynthetic reinforcement of aggregate base courses in pavements. However, the many variables that are input into a life-cycle cost analysis, as well as regional variables, such as aggregate cost and pavement designs, require agency-specific or project-specific assessment of economic viability of base course reinforcement. Geosynthetic reinforcement will provide substantial *value-added* benefits for some combinations of conditions, and will not be cost effective for other combinations of conditions. Guidance on the conditions under which geosynthetic aggregate base reinforcement provides *value-added* benefits to pavement structures is provided in Section 4. Cost saving benefits should be quantified using life-cycle analyses. Just examining initial construction costs oversimplifies the economic evaluation. Life-cycle cost analyses will invariably show a greater cost savings than initial construction cost analysis. Example life-cycle cost analyses are presented in Section 6.

Recommended practice, in the form of step-by-step design procedures, for incorporating geosynthetic base course reinforcement into a pavement design are presented in Section 8. Geosynthetic reinforcement is being used in roadways to aid in support of traffic loads, where loads may be due to vehicular traffic over the life of the pavement or equipment loads on the unpaved base course during construction. The type of load to be supported dictates the approach to design, and the resulting material specification. Function, or design, of the geosynthetic reinforcement can be categorized as either *base (or subbase) reinforcement* or as *subgrade restraint*.
Base (or subbase) reinforcement is typically applied to support vehicular traffic over the life of a pavement structure. Base reinforcement design (Section 8.3) utilizes an empirically derived traffic benefit ratio (TBR), base course reduction ratio (BCR), or layer coefficient ratio (LCR) to quantify contribution of the geosynthetic reinforcement. These ratios are specific to the product, material,

geometry, failure criteria, and load used in the tests to quantify their values. Therefore, the user must assess applicability of proposed ratios of various products to their agency or project-specific materials, geometry, failure (or rehabilitation) criteria, and loading. Guidance for assessing applicability is provided within Section 8 and Appendix E.

Although the research strongly supports the design procedure contained herein, long-term performance information of projects based on these procedures are not available at this time such that confidence limits can be established. Therefore, it is recommended that agencies with limited geosynthetic reinforcement experience primarily use the reinforcement to improve the service life of pavement structures, and limit reduction of the structural section until more local experience is gained.

Subgrade restraint design is the use of a geosynthetic placed at the subgrade/subbase or subgrade/base interface to increase the support of construction equipment over a weak or soft subgrade. The primary mechanism with this application is increased bearing capacity. Often accompanying the reinforcing function for this application is a need for separation and filtration. Recommended practice for subgrade restraint reinforcement design is summarized in Section 8.4.

For some projects, particularly those with a base and subbase, two layers of geosynthetic reinforcement may be used to provide both subgrade restraint and base reinforcement. Each layer of reinforcement be independently designed for such applications.

Recommended practice for specification of geogrid, geotextile, and geogrid-geotextile composite reinforcements is presented within Appendix D, in the form of editable material specifications. For base reinforcement designs, an approved product list approach is recommended, as the mechanisms of reinforcement are not fully understood and the TBR, BCR, or LCR ratios should be considered product, and test conditions, specific. Equivalent materials must demonstrate equivalent performance in test structures and/or possess equivalent material properties, as selected by the specifier.

Subgrade restraint design procedures are based upon either (i) generic material properties, wherein a generic specification can be prepared based upon those design property requirements; or (ii) product-specific, empirically derived design methods, wherein an approved product specification approach may be used. Alternatively, specifications may use an approved products list, with equivalency defined.

This white paper provides government agencies with current, logical recommended practice for the systematic use of geosynthetic reinforcement of pavement base courses. Refined guidance should be developed as the use of base reinforcement increases and additional long-term performance data becomes available.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

[BLANK]

1.0 INTRODUCTION

1.1 BACKGROUND

A new task group of the American Association of State Highway Transportation Officials (AASHTO) Subcommittee on Materials Technical Section 4E was formed in 1997. Task group meetings have been held during the 1998 and 1999 Transportation Research Board (TRB) annual (January) meetings. The overall goal of this AASHTO 4E Task Group is the development of AASHTO specification(s) for geosynthetic reinforcement of the aggregate base course of pavement structures.

To aid in the development of such specifications, the Geosynthetic Materials Association (GMA) sponsored development of this report, referred to as the GMA White Paper II. The goal of this report is to document the conditions under which geosynthetic reinforcements provide *value-added* benefits to pavement structures when the geosynthetic is contained at the bottom of, or within, the aggregate base (or below the subbase). Specific objectives of this report include documentation of the following:

- Value added to pavements in reinforcement of the pavement structure;
- Design criteria/protocol(s); and
- Practices for design and material specification.

This second GMA white paper was prepared to complement the first GMA white paper. The first white paper, *Geosynthetics in Pavement Systems Applications*, completed May 1999, primarily focused on survivability of geogrids and geotextiles in pavement reinforcement applications. The specifications presented within this white paper are modifications of the specifications presented in the first white paper and, therefore, supercede those prior specifications. The generic material specification approach presented in the first white paper is not always suitable, as documented herein.

The AASHTO 4E Task Group anticipates another study and report on this subject. Funds have been requested to perform a TRB synthesis on geosynthetic pavement system reinforcement. This proposed synthesis would address the following:

1. Scope — requires a worldwide search for pertinent information that will document *value-added* benefits by incorporating geosynthetics as reinforcement in roadway sections. The synthesis should include, but not be limited to:
    a. Current Practice(s)
    b. Critique of Existing Design Methodologies

   c. Constructability & Survivability of Installation Issues
   d. Evaluation of Performance
   e. Future Research Needs
2. Limitations — not stated

This white paper will provide a good complement to a complete synthesis on geosynthetic pavement system reinforcement. When combined with the first GMA white paper (GMA WP I), focused on installation and construction damage, practically all the essential elements of a synthesis are covered, including current practice, existing design methodologies, performance evaluation, and future research needs. However, a complete synthesis would allow for more interaction with agencies incorporating this practice, offer the opportunity to obtain a more comprehensive survey of current practice, and would critically review reported research.

1.2 GMA WHITE PAPER II

1.2.1 Purpose and Objectives

The purpose of this report is to provide documentation to the AASHTO 4E Task Group on the value added to pavement systems when geogrid, geotextile, and/or geogrid-geotextile composite are used for: (i) base or subbase course reinforcement over soft subgrades; and (ii) base course reinforcement over moderate to firmer subgrades. The objectives of the GMA in sponsoring this work are summarized below:

1. Provide documentation that permits a consensus to be reached that there is value added to pavements when geogrids, geotextiles, and geogrid-geotextile composites are used in reinforcement of a: (i) base or subbase course over soft subgrades; and (ii) base course over moderate to firmer subgrades.
2. Document benefits of geogrid, geotextile, and geogrid-geotextile composite reinforcement of a: (i) base or subbase course over soft subgrades; and (ii) base course over moderate to firmer subgrades.
3. Document and critique available design procedures for geogrid, geotextile, and geogrid-geotextile composite reinforcement of a: (i) base or subbase course over soft subgrades; and (ii) base course over moderate to firmer subgrades.
4. Document under what conditions geogrid, geotextile, and geogrid-geotextile composite reinforcement of base or subbase course over soft subgrades and base course over moderate to firmer subgrades are: (i) beneficial; and (ii) not beneficial.
5. Document potential cost-benefits of geogrid, geotextile, and geogrid-geotextile composite reinforcement of a base or subbase course over soft subgrades and base course over moderate to firmer subgrades using available design procedures.

6. Distinguish between geotextile separation and stabilization applications (addressed with the AASHTO M288 specification) and the reinforcement applications addressed within the white paper.
7. Summarize completed geosynthetic pavement reinforcement research (with the exclusion of asphalt reinforcement).
8. Discuss/summarize research needs.
9. Summarize what geogrid, geotextile, and geogrid-geotextile composite material properties seem to be the most influential in providing a benefit to the pavement structure, based upon the literature review.
10. Document current recommended practice (i.e., design approach, specification approach, etc.) for geogrid, geotextile, and geogrid-geotextile composite reinforcement of base or subbase course over soft subgrades and base course over moderate to firmer subgrades. It is anticipated that documented current practice will require refinement as additional research is conducted and as the use of geosynthetic products for reinforcement is expanded.
11. Develop proposed material specifications for geogrid, geotextile, and geogrid-geotextile composite reinforcement of base or subbase course over soft subgrades and base course over moderate to firmer subgrades. Revise specifications from GMA White Paper I.
12. Develop an external report produced by authors (who are members of the 4E AASHTO Task Group) who are independent of GMA (i.e., not GMA members).

1.2.2 Organization

This white paper is organized by topic sections. An Executive Summary precedes the report. Section 1 contains background information; purpose, objectives, and scope of this paper; applications and materials addressed; terminology; and a usage guide. Subsequent section discussions are organized by permanent paved roads and other applications (temporary paved, temporary unpaved, and permanent unpaved roads); low or moderate to firmer subgrade; and geosynthetic material type.

A limited literature survey is presented in Section 2. The review is limited to literature from or directly related to North American pavement practices. Information on general benefits of, value added with, favorable conditions for use of, important material properties of, and design procedures for, geosynthetic reinforced pavements from the literature are summarized.

General potential benefits of geosynthetic reinforcement are presented in Section 3. Benefits are presented for paved and unpaved roads, and temporary and permanent roads, over soft and moderate to firmer subgrades. Applicability of reinforcement to permanent paved roads is summarized in Section 4. Use of reinforcement for other applications (i.e., permanent unpaved, temporary unpaved, and temporary paved) are also presented.

Design approaches and procedures are reviewed and discussed in Section 5. Permanent paved roads and other applications are addressed. Potential cost benefits of geosynthetic reinforcement are discussed for permanent paved roads in Section 6. Potential initial and life-cycle cost benefits are quantified for a variety of assumed conditions. Cost benefits for other applications are discussed, but not quantified.

Geosynthetic material properties for pavement reinforcement are reviewed in Section 7. Identified properties are classified as either being potentially influential, required for performance characterization, or required for construction survivability. Properties are listed for paved permanent roads, and discussed for other applications.

Recommended practices for geosynthetic pavement reinforcement are presented in Section 8. Recommended design procedures, specification approaches, and guideline material specifications for geogrids, geotextiles, and geogrid-geotextile composites are presented. The specifications are for permanent paved roads, and are based upon revision of specifications presented in the GMA White Paper I. Components of specifications for other applications are discussed.

A discussion of benefits, applicability, economics, and material properties; research needs; and conclusions are presented in Sections 9, 10, and 11, respectively.

1.2.3 Work Excluded from Scope

The work scope for GMA White Paper II followed the stated and agreed upon, goals and objectives as documented above and is, therefore, limited by such. Information from the literature survey is taken at face value, and is not synthesized or critiqued. The work scope excludes development of data bases: on DOT applications of geosynthetic pavement reinforcements and performance case histories, geosynthetic reinforcement of asphalt, use of geocell materials; and revision of the GMA White Paper I. Furthermore, application of geosynthetic reinforcement with marginal or recycled base course materials is not addressed. Note, however, that the use of marginal and recycled materials with geosynthetic reinforcement is a promising application of geosynthetics.

1.3 APPLICATIONS AND MATERIALS

1.3.1 Applications

This white paper is focused on the primary application of geosynthetic reinforcement of the aggregate base course of pavement, permanent roadways. Other applications of reinforcement of subbase and subgrade restraint are also reviewed and discussed, as appropriate.

1.3.2 Materials

Use of good quality base course, either well-graded or open-graded, is assumed within this paper. The distinction is noted to clarify when a filter between the subgrade and base course may be required. The filter requirement may be met with a geotextile or with a sand subbase. Pavements may be founded upon a low, a moderate, or a firmer subgrade, as described within. Geosynthetic pavement inclusions addressed within this white paper are: geogrids; geotextiles; and geogrid-geotextile (GG-GT) combinations. GG-GT combinations may be manufactured composites or constructed in the field with placement of a geogrid over a geotextile. Materials addressed in this paper are listed in Table 1-1. Potentially, these materials can be used with all of the applications. However, the conditions better suited to the use of various reinforcements are examined and summarized within this paper.

Table 1-1. Pavement Reinforcement Materials

COMPONENT	MATERIALS	
Aggregate Base or Subbase	Well-Graded	
	Open-Graded	
Subgrade	Low	
	Moderate	
	Firmer	
Geosynthetic Reinforcement	Geogrid (within or under base (or subbase))	Extruded
		Knitted or Woven
	Geotextile (under base (or subbase))	Woven
		Nonwoven
	Geogrid-Geotextile Composite (under base (or subbase))	Bonded
		Unbonded
NOTE: See Section 1.4 for definition of terms used within this paper.		

1.4 TERMINOLOGY AND DEFINITIONS

1.4.1 GMA White Paper II

The following definitions are used in this paper to define the geosynthetic reinforcement applications in roads.

- Pavement System Reinforcement — Use of a geosynthetic to aid in support of traffic loads, where loads may be vehicular loads over the life of the pavement, or construction equipment loads on the unpaved base course or subbase during construction.

- Base Reinforcement — Base (or subbase) reinforcement may occur when a geosynthetic is placed as a tensile element at the bottom of a base (or subbase) or within a base course to: (1) improve the service life and/or; (2) obtain equivalent performance with a reduced structural section. The mechanisms of reinforcement leading to these two benefits are described in detail in Section 2.4. Base reinforcement is applicable for the support of vehicular traffic over the life of the pavement and is designed to address the pavement distress mode of permanent surface deformation or rutting and asphalt fatigue cracking.
- Subgrade Restraint — Subgrade restraint may occur when a geosynthetic is placed at the subgrade/subbase or subgrade/base interface to increase the support of construction equipment over a weak or low subgrade. The primary mechanism with this application is increased bearing capacity, although lateral restraint and/or tension membrane effects may also contribute to load-carrying capacity. Subgrade restraint is the reinforcing component of stabilization as defined in Section 1.4.2.

Geosynthetics used in pavement systems include woven and nonwoven geotextiles, geogrids, and GG-GT composites. Geogrids and geocomposites are further divided into these categories:

- Extruded Geogrid — geogrids manufactured with integral junctions in an extrusion process, typically manufactured of polypropylene, polyethylene, or a copolymer of the two.
- Knitted or Woven Geogrid — geogrids manufactured with fibers, usually polyester or polypropylene, and coated.
- Welded Geogrid – geogrids manufactured with extruded polyester, polypropylene or polyethylene bars that are welded together at crossover points. {Note: not discussed in this document due to lack of published research data.}
- Bonded GG-GT Composite — a manufactured geogrid-geotextile composite that is shipped and installed as a composite.
- Unbonded GG-GT Composite — a field-constructed composite, where a geogrid is laid over a geotextile.

As used in this paper, the subgrade strength, in the context of its behavior under loading by (i) normal highway (truck) traffic, or (ii) typical highway construction equipment is defined as follows:

- Firmer Subgrade — a subgrade with a CBR value greater than approximately eight ($CBR > 8$) (shear strength equal to or greater than approximately 240 kPa; resilient modulus greater than approximately 80 MPa).
- Moderate Subgrade — as defined within this paper, a subgrade with a CBR value equal to or between approximately three and eight ($3 \leq CBR \leq 8$) (shear strength between approximately 90 kPa and 240 kPa; resilient modulus between approximately 30 MPa and 80 MPa).

- Low Subgrade — as defined within this paper, a subgrade with a CBR value approximately less than three (CBR < 3) (shear strength equal to or less than approximately 90 kPa) (resilient modulus less than approximately 30 MPa).

The base and subbase terms, as used within, are defined below:
- Base — the portion of the flexible pavement structure immediately beneath the asphalt surface course, consisting of unbound aggregates, such as crushed stone or crushed gravel and sand.
- Subbase — the portion of the pavement structure between the subgrade and base course.

Roads and highways are broadly classified as permanent and temporary.
- Permanent Roads — paved and unpaved systems usually remaining in service for ten years or more.
- Temporary Roads — unpaved or paved (e.g., construction bypass) systems with a short service life, usually less than one year.

The functions of geosynthetics in roadways include these uses:
- Separation — prevention of subgrade soil intruding into aggregate base (or subbase), and prevention of aggregate base (or subbase) migrating into the subgrade.
- Filtration — restricting the movement of soil particles, while allowing water to move from the filtered soil to the coarser soil adjacent to it during the performance life of the structure.
- Lateral Drainage (i.e., transmission) — the lateral movement of water within the plane of the geosynthetic.
- Reinforcement — the addition of structural or load-carrying capacity to a pavement system by the transfer of load to the geosynthetic material.

The mechanisms by which geosynthetics provide reinforcement include the following:
- Lateral Restraint — a pavement reinforcement mechanism, see Figure A-2 and Section 2.4. Components of this mechanism can include: (i) restraint of lateral movement of base, or subbase, aggregate (confinement); (ii) increase in modulus of base aggregate due to confinement; (iii) improved vertical stress distribution on subgrade due to increased base modulus; and (iv) reduced shear strain along the top of the subgrade.
- Bearing Capacity Increase — a pavement reinforcement mechanism, see Figure A-2.
- Tensile Membrane Support— a pavement reinforcement mechanism mobilized under high deformation conditions, see Figure A-2.

The improvement to the pavement system provided by geosynthetic reinforcement is directly measured by a TBR or BCR ratio.
- TBR — Traffic benefit ratio: A ratio of the number of load cycles on a reinforced section to

reach a defined failure state to the number of load cycles on an unreinforced section, with the same geometry and material constituents, to reach the same defined failure state. TBR is sometimes termed traffic improvement factor (TIF).

- BCR — Base course reduction: The percent reduction in the reinforced base, or subbase, thickness from the unreinforced thickness, with the same material constituents, to reach the same defined failure state.

A pavement reinforcement design term, used in some procedures, is LCR.

- LCR — Layer coefficient ratio: A modifier applied to the layer coefficient of the aggregate. This value is back-calculated, based upon the number of load cycles on a reinforced section to reach a defined failure state to the number of load cycles on an unreinforced section, with the same geometry, to reach the same defined failure state.

1.4.2 AASHTO M288 Specification

Geotextile Separation — The separation application is appropriate for pavement structures constructed over soils with a California Bearing Ratio equal to or greater than 3 (CBR $\geq$ 3) (shear strength greater than approximately 90 kPa). It is appropriate for unsaturated subgrade soils. [Note that a geotextile separator also may be appropriate for open-graded base materials reinforced with a geogrid.]

Geotextile Stabilization — stabilization is applicable to the use of a geotextile in wet, saturated conditions to provide the coincident functions of separation and filtration. In some installations, the geotextile can also provide the function of reinforcement [though stabilization design procedures normally assume no reinforcement contribution]. Stabilization is applicable to pavement structures constructed over soils with a California Bearing Ratio between one and three (1 < CBR < 3) (shear strength between approximately 30 kPa and 90 kPa).

Applicable excerpts of the AASHTO M288 (1997) specification for geotextile separation and stabilization are included in Appendix B.

1.5 HOW TO USE THIS WHITE PAPER

One of the objectives of this paper are to demonstrate the value-added benefits from using geosynthetic reinforcement in pavements and to document recommended practice for users. Users (or potential users) of geosynthetic reinforcement can, generally, refer to the recommended practice presented in Section 8. A step-by-step design procedure, which is adaptable to both agency-specific pavement design procedures and to reinforcement product-specific design procedures, is presented. Material specifications also are presented for geogrids, geotextiles, and geogrid-geotextile composite reinforcements. Edit notes are listed within the specifications. Approved product list specification and a format for generic material specification are presented and discussed. Sections preceding and following Section 8 provide supporting information for recommended design procedures and specifications.

The value-added benefits of geosynthetic reinforcement are summarized in Section 6, and example life-cycle cost analyses are presented. Agency-specific life-cycle cost analyses are recommended for quantifying cost savings of geosynthetic reinforcement of paved, permanent roadways. Supporting information for the value-added benefits, design, and specification discussions are presented in preceding sections. Literature on geosynthetic reinforcement is summarized and reviewed in Section 2. Benefits of geosynthetic reinforcement are described in Section 3. Applicability of geosynthetic reinforcement is outlined in Section 4. Design methodologies are summarized in Section 5.

A discussion of the current state of practice is presented in Section 9. Research needs are summarized in Section 10. Conclusions regarding recommended practice and supporting documentation for base reinforcement with geosynthetics are summarized in Section 11. Supporting information is appended, including a recommended procedure for documentation of geosynthetic reinforcement benefit by test section evaluation.

[BLANK]

2.0 LITERATURE REVIEW

2.1 PURPOSE OF REVIEW

The purpose of this review is to introduce and summarize literature pertaining to the application of geosynthetics as reinforcement in a flexible pavement structure, by examining performance of experimental pavement test sections. The review is limited to published research reports, journal articles, and conference proceedings. Only work of a research nature is reviewed in this section. Research work is defined as that which examines and describes the benefits derived by use of geosynthetic reinforcement, usually as compared to similar or equivalent test sections not containing reinforcement. Work of a research nature also implies that the work was scientifically documented. Implementation of this technology is presented in Section 8.

Literature summarized in this section is limited (except where noted otherwise) to work involving the construction and evaluation of flexible pavement test sections where geotextiles, geogrids, or geogrid-geotextile composites have been placed within or at the bottom of the base or subbase of the pavement structure for the purpose of reinforcement. Work pertaining to unpaved roads is cited only if the work illustrates certain features pertinent to flexible pavements. This review is structured to illustrate the value added to flexible pavements by the use of geosynthetic reinforcement. In particular, the review is designed to illustrate the benefits derived from geosynthetic reinforcement, the conditions under which reinforcement is beneficial, the geosynthetic properties that are most influential for this application, and the mechanisms responsible for reinforcement. Conclusions from this section are used later to evaluate existing design procedures, to comment on potential cost benefits, and to develop application specifications.

All work reviewed in this section is taken at face-value, meaning that the work has not been critiqued in the process of review. Every attempt has been made to report details and conclusions as contained in the original references. Given the desire to compare common variables and performance-related parameters between research studies, it was sometimes necessary to infer those variables and parameters from other information in the studies.

The level of detail reported in the studies summarized in this section varies. Users of geosynthetic reinforcement are encouraged to refer to the original documents to determine applicability of the research to their project. As a guide for critiquing these studies, readers should look for information pertaining to the following:

1. Documentation pertaining to quality control measures taken during construction of test sections and the results of those measures. Quality control measures may include:

a. In-place dry density and water content of compacted layers.
b. In situ measurements of subgrade strength properties.
c. Coring and sampling of representative asphalt concrete materials.
d. Appropriate laboratory tests to establish the range of material parameters over the range of conditions achieved during the construction process.

2. Replicate test sections and the degree to which results could be repeated.
3. The type, quantity, and degree of sophistication associated with measurements taken to establish performance benefits.
4. The existence of construction- or material-related problems that may have influenced performance benefits.

2.2 SUMMARY OF PUBLISHED LITERATURE

Studies that have been reviewed and that contain the desired information outlined in Section 2.1 are listed in Table 2-1. In some cases, several publications present material that is viewed as part of one study. The studies examined fall within the category of research studies involving reinforced pavement test sections. Only studies supplying the majority of the information contained in tables included in this section and that provide insight into potential benefits of geosynthetics as reinforcement have been examined. In addition, only studies involving test sections with paved roadways are examined and discussed in Sections 2.1 through 2.4. Related research on unpaved roads is discussed in Section 2.5.

Information on the type of pavement test facility used for each study is provided in Table 2-2. Information on the thickness and material types used for the asphalt, base, subbase, and subgrade layers of the test sections for each study are presented in Table 2-3. The geotextiles and geogrids used in all the studies reviewed are listed in Tables 2-4 and 2-5. Table 2-6 lists the specific geosynthetic products and location within the base or subbase layer for each study. Geosynthetic products listed in Tables 2-4 and 2-5 have been assigned alphabetic names that are used throughout the remainder of this section. In the studies reviewed, combinations of specific geogrids and geotextiles were used in one test section, but no specific geogrid-geotextile composite materials were used.

As noted in Table 2-2, a variety of pavement test facilities have been used, with applied pavement loads ranging from a stationary circular load plate (where a cyclic load is applied) to actual truck traffic. Pavement load magnitude has varied considerably, ranging from loads as light as 0.42 kN to 130 kN. The range in thickness of pavement layers has been 20-180 mm for the asphalt concrete (AC) layer and 40-640 mm for the combined base/subbase system. Subgrade strength, as measured by the California Bearing Ratio (CBR), has ranged from 0.5 to 27. Study test sections were categorized by subgrade, defined as low, moderate, and firmer. These are defined by strengths of CBR < 3, 3 ≤ CBR ≤ 8, and CBR > 8, respectively.

Table 2-1. Studies and Corresponding References of Literature Reviewed

Study	References
Al-Qadi (lab)	Al-Qadi et al. (1994), Smith et al. (1995), Al-Qadi et al. (1997)
Al-Qadi (field)	Brandon et al. (1995), Brandon et al. (1996), Al-Qadi et al. (1997), Al-Qadi et al. (1998), Appea et al. (1998), Bhutta et al. (1998)
Anderson	Anderson and Killeavy (1989)
Barker	Barker (1987)
Barksdale	Barksdale et al. (1989), Chan et al. (1989), Chan (1990)
Brown	Brown et al. (1982), Brown et al. (1983)
Cancelli (lab)	Cancelli et al. (1996), Montanelli et al. (1997)
Cancelli (field)	Cancelli et al. (1999)
Collin	Collin et al. (1996)
Haas	Penner (1985), Carroll et al. (1987), Haas et al. (1988)
Halliday	Halliday and Potter (1984)
Humphrey	Fetten et al. (1998), Hayden et al. (1999)
Huntington	Huntington and Ksaibati (1999)
Kinney	Kinney et al. (1998a,b)
Miura (lab)	Miura et al. (1990)
Miura (field)	Miura et al. (1990)
Perkins	Perkins and Ismeik (1997a,b), Perkins et al. (1998a,b; 1999), Perkins (1999a,b)
Small	Moghaddas-Nejad and Small (1996)
Webster	White (1991), Webster (1992, 1993)
Note: Tables 2-2 through 2-7 provide details of the studies listed in Table 2-1.	

Table 2-2. Test Section Type and Loading

Study	Type of Facility	Facility Dimensions[1] (m)	Test Section Length (m)	Load Type	Applied Cyclic Pressure (kPa)	Applied Cyclic Load (kN)	Load Frequency or Wheel Speed
Al-Qadi (lab)	Laboratory tank	3.1 x 1.8 x 2.1	NA[2]	Stationary circular plate, 300 mm diameter	550	39	0.5 Hz
Al-Qadi (field)	Public roadway	135	15	Random public traffic	Random	Random	Random
Anderson	Field truck staging area	Outdoor staging area	NA	Loaded truck traffic of various types	Random	Random w/ axle loads up to 130	65-70 vehicles/ week
Barker	Outdoor test track	21 x 4.6 x 1.1	4.6	Moving single wheel	1826	120	NR[2]
Barksdale	Indoor test track	4.9 x 2.4 x 1.5	1.6	Moving single wheel	460-500	6.6	1.3 m/s
Brown	Indoor test track	4.9 x 2.4 x 1.5	NR	Moving single wheel	530	5-11	1.3 m/s
Cancelli (lab)	Laboratory tank	0.9 x 0.9 x 0.9	NA	Stationary circular plate, 300 mm diameter	570	40	5 or 10 Hz
Cancelli (field)	Outdoor test track	210 x 4 x 1.2	4.0	Single wheel front axle and double wheel rear axle truck	800	45 front axle, 90 rear axle, 22.5 per wheel	5.6 m/s
Collin	Indoor test track	14.6 x 4.4 x 1.2	3.4	Moving single wheel	550	20	1.2 m/s
Haas	Laboratory tank	4.5 x 1.8 x 0.9	NA	Stationary circular plate, 300 mm diameter	550	40	8 Hz
Halliday	Outdoor test track	20 x 4.25 x 1.5	10.0	Single wheel front axle and double wheel rear axle truck	760	49 and 68 per rear wheel	1.4 -2.2 m/s
Humphrey	Public roadway	3 km road	231	Random public traffic	Random	Random	Random
Huntington	Public roadway	2.9 km road	1900 to 270	Random public traffic	Random	Random	Random

Table 2-2. Test Section Type and Loading (cont.)

Study	Type of Facility	Facility Dimensions[1] (m)	Test Section Length (m)	Load Type	Applied Cyclic Pressure (kPa)	Applied Cyclic Load (kN)	Load Frequency or Wheel Speed
Kinney	Indoor test track	19.5 x 2.4 x 1.2	6.1	Moving single wheel (& FWD)	551, 276	20	1.2 m/s
Miura (lab)	Laboratory tank	1.5 x .15 x 1.0	NA[2]	Stationary circular plate, 200 mm diameter	200	6.3	0.18 Hz
Miura (field)	Public roadway	300 m road	50.0	Random public traffic	Random	Random	Random
Perkins	Laboratory Tank	2 x 2 x 1.5	NA	Stationary circular plate, 300 mm diameter	550	40	0.67 Hz
Small	Indoor test track	1.4 x 0.5 x 0.8	1.4	Moving single wheel	210	0.42	0.74 m/s
Webster	Covered outdoor test track	44 x 3.8 x 1.0	11.0	Moving single wheel	470	130	NR[2]

Notes: 1. Length x Width x Depth, unless otherwise listed.
2. NA = Not Applicable; NR = Not Reported.

Table 2-3. Test Section Layers and Properties

Study	Layer Thickness (mm)			Layer Material Types		
	AC	Base	Subbase	Base	Subbase	Subgrade (CBR)
Al-Qadi (lab)	70	150, 200	None	GW-GM, A-1-a	None	SM, A-4 (2, 4)
Al-Qadi (field)	90	100, 150, 200	None	GW	None	CH, A-7-6 and ML, A-5 (7)
Anderson	105	200, 350	None	Crushed limestone	None	Soft silt and clay with organic pockets
Barker	75	150	150	GP, A-1-a	Cement treated sandy gravel	Sandy silt (27)
Barksdale	25, 38	150, 200	None	GP, A-1-b and GP-GM, A-1-a	None	CL, A6 (2.5, 3.2)
Brown	37-53	107-175	None	GW, A-1-a	None	CL, A6 (2-8)
Cancelli (lab)	75	300	None	GW, A-1-a	None	SP, A-3 (1, 3, 8, 18)
Cancelli (field)	75	300, 400, 500	None	Gravel	None	CL, A-6 (1, 3, 8)
Collin	50	150-460 tapered	None	GW, A-1-a	None	CL (1.9)
Haas	75, 100	100, 150, 200, 250, 300	None	GW, A-1-b	None	SP, A-3 (8, 3.5) and fine sand mixed with peat (1, 0.5)
Halliday	160	300	None	Crushed granite	None	CH, A-7-6 (0.7-4.3)
Humphrey	180	580, 640	None	GW, A-1-a	None	CL, A-6 (3)
Huntington	100	280, 430	None	GW, A-1a, 50% RAP	None	Design subgrade support = 4.3, CBR = 4
Kinney	61	150-530 tapered	None	Crushed rock	None	CL (2.5)
Miura (lab)	50	150	200	NR[1]	NR	Sensitive clay slurried and consolidated by 5 or 10 kPa
Miura (field)	50	150, 200	200, 250	NR	NR	600-800 mm compacted mine tailings (4-6) over soft clay
Perkins	75	200, 300, 375	None	GW, A-1-a	None	SM, A-4 (15), CH, A-7-6 (1.5)
Small	20	40	None	SP, A-1-a	None	SP, A-3
Webster	50	150, 250, 300, 350, 450	None	SM-SC, A-1-a	None	CH, A-7-6 (3, 8)
Note: 1. NR = Not Reported.						

Table 2-4. Properties of Geotextiles Used in Test Studies

Geotextile	Manufacturer, Product Name	Structure[1]	Polymer Composition[2]	Identifying Properties[3]		
				Mass/Unit Area (g/m^2)	Secant Modulus MD/XMD (kN/m)	
					2%	5%
A	Amoco 2002	W	PP	120	NR[4]	200/310
B	Amoco 2016	W	PP	190	NR	228/420
C	Nicolon HP570	W	PP	970	NR	NR/750
D	NR	W-MF	PET	NR	NR	NR
E	Amoco 6070	W	PP	250	NR	196/412
G	Terram 7M7	NW-HB substrate reinforced with polyester yarn	PET	NR	NR	NR
H	Terram 1000	NW-HB	PP and PE	NR	NR	32[5]
I	Amoco 2006	W	PP	250	NR	200/440
J	Nicolon HP67809	W	PP	500	NR	350/700
K	TC Mirafi 180N	NW-P	PP	270	NR	20[5]
L	Terrafix 270R	NW-P	NR	NR	NR	10[5]

Notes:
1. W = Woven, NW = Nonwoven, P = Needlepunched, HB = Heat Bonded, MF = Multifilament.
2. PP = Polypropylene, PET = Polyester, PE = Polyethylene.
3. Typical property values from manufacturers' literature, research reports, or from manufacturers.
4. NR = Not Reported.
5. Estimate based on testing of similar materials.

Table 2-5. Properties of Geogrids Used in Test Studies

Geo-grid	Manufacturer, product name	Structure[1]	Polymer Composition[2]	Identifying Properties[3]					
				Mass/ Unit Area (g/m²)	Aperture Size MD/XMD (mm)	Secant Modulus MD/XMD (kN/m)		Secant Aperture Modulus[4] (cm-kg/deg)	Flexural Rigidity[5] (g-cm)
						2%	5%		
A	Tensar, BX 1100	PSDB	PP	203	25/36	NR[6]	120/260	4.2	250
B	Tensar, BX 1200	PSDB	PP	306	25/33	NR	220/400	8.5	750
C	Tensar, BX 1300	PSDB	PP	247	46/64	NR	220/340	NR	450
D	Quline, FORTRAC 35/20-20	W	PET/PVC-C	235	20/20	NR	248/167	2.0	NR
E	Mirafi, Miragrid 5T	W	PET	270	30/33	NR	227/124	2.2	NR
F	Tenax, LBO 201 SAMP	BCEO	PP	230	32/40	NR	160/216	NR	NR
G	Conwed, GB-3022	K	PET/PVC-C	193	18/19	NR	218/161	3.4	NR
H	Tenax, MS 220	MBCEO	PP	240	42/50	NR	180/260	NR	250
I	Tenax, MS 1000	BCEO	PP	250	30/40	NR	180/260	NR	NR
J	Tenax, LBO 301 SAMP	BCEO	PP	350	30/40	NR	200/370	NR	NR
K	Tenax, MS 330	MBCEO	PP	360	42/50	NR	270/392	NR	750
L	Tenax, MS 500	MBCEO	PP	315	60/60	NR	270/392	NR	750
M	Monsanto[7]	PSDB[7]	PP	NR	15/15	NR	NR	NR	NR

Notes:
1. PSDB = Punched, sheet drawn, biaxial, W = Woven, K = Knitted, BCEO = Biaxial, continuous extrusion and orientation, MBCEO = Multilayer, biaxial, continuous extrusion and orientation.
2. PP = Polypropylene, PET = Polyester, PVC-C = Polyvinyl chloride coated.
3. Typical property values from manufacturers' literature, research reports, or from manufacturers.
4. Secant aperture stability modulus as defined in Webster (1993).
5. Flexural rigidity per modified ASTM D 1388 (discontinued 1995).
6. NR = Not Reported.
7. Experimental product. Geogrid contained 6.4 mm posts extending up from ribs.

Table 2-6. Type and Location of Geosynthetic Used in Each Study

Study	Geosynthetic	Location with respect to base course layer
Al-Qadi (lab)	Geotextile A Geotextile B Geogrid B	Bottom Bottom Bottom
Al-Qadi (field)	Geotextile A Geogrid B	Bottom Bottom
Anderson	Geogrid A and Geotextile L Geotextile L	Bottom, geogrid over geotextile
Barker	Geogrid B	Middle
Barksdale	Geotextile C Geogrid A	Middle, Bottom Middle, Bottom
Brown	Geotextile G Geotextile H	Bottom Bottom, Bottom and Middle
Cancelli (lab)	Geotextile E Geogrid A, D, I, J Geogrid H	Bottom Bottom Bottom, Bottom and Middle
Cancelli (field)	Geotextile E Geogrid A Geogrid B Geogrid H Geogrid K Geogrid L	Bottom Bottom Bottom Bottom Bottom Bottom
Collin	Geogrid A Geogrid B	Bottom Bottom
Haas	Geogrid A	Top, Middle, Bottom
Halliday	Geotextile D	Bottom
Humphrey	Geotextile J Geotextile K Geogrid K	Bottom Bottom Bottom, near middle, Bottom and near middle
Huntington	Geogrid A	Middle
Kinney	Geogrid B Geogrid M	Bottom Bottom
Miura (lab)	Geogrid A Geogrid B Geogrid C	Bottom and bottom of subbase, Bottom and middle of base Bottom, Bottom of subbase Bottom of subbase
Miura (field)	Geogrid B Geogrid C	Bottom, Bottom of subbase Bottom, Bottom of subbase

Table 2-6. Type and Location of Geosynthetic Used in Each Study (cont.)

Study	Geosynthetic	Location with respect to base course layer
Perkins	Geotextile I Geogrid A Geogrid B	Bottom Bottom, 1/3 up in base Bottom
Small	Geogrid B	Bottom, Middle
Webster	Geogrid A Geogrid B Geogrid D Geogrid E Geogrid F Geogrid G	Bottom Bottom, Middle Bottom Bottom Bottom Bottom

Table 2-7. Studies Using a Subgrade Classified as Low, Moderate, or Firmer

Study	Subgrade Condition		
	Low (CBR < 3)	Moderate (3 ≤ CBR ≤ 8)	Firmer (CBR > 8)
Al-Qadi (lab)	2	4	—
Al-Qadi (field)	—	7	—
Anderson	NR[1]		
Barker	—	—	27
Barksdale	2.5	3.2	—
Brown	2	4, 5, 8	—
Cancelli (lab)	1	3, 8	18
Cancelli (field)	1	3, 8	—
Collin	1.9	—	—
Haas	0.5, 1	3.5, 8	—
Halliday	0.7	4.3	—
Humphrey	—	3	—
Huntington	—	4	—
Kinney	2.5	—	—
Miura (lab)	NR		
Miura (field)	—	4 to 6	—
Perkins	1.5	—	15
Small	NR		
Webster	—	3, 8	—
Note: 1. NR = Not Reported.			

2.3 DEMONSTRATION & DISCUSSION OF VALUE ADDED BY REINFORCEMENT

Measured benefits from the studies reviewed are presented in Tables 2-8, 2-9, and 2-10. Benefit, or value-added, is expressed in terms of extension of life or by savings in base course thickness. Extension of life is defined in terms of a Traffic Benefit Ratio (TBR). TBR is defined as the ratio of the number of cycles necessary to reach a given rut depth for a test section containing reinforcement, divided by the number of cycles necessary to reach this same rut depth for an unreinforced section with the same section thickness and subgrade properties. Rut depths used for the determination of respective TBR values are listed in Tables 2-8, 2-9, and 2-10. A TBR > 1 also provides a safety factor on the pavement load-carrying capacity against significantly increased EASLs or weaker subgrade from design values. The base course reduction (BCR) is expressed as a percentage savings of the unreinforced base thickness. Information on base course reduction is extracted from those studies where unreinforced and reinforced test sections with equal AC thickness and subgrade were created, but where the reinforced section contained less base course material and resulted in identical performance.

Tables 2-8, 2-9, and 2-10 list specific test sections from studies that determined TBR or base course reduction percentage. Thickness of the AC, base and subbase, and subgrade CBR for each test section are listed. For cases where a percentage base course reduction is listed, the base thickness corresponds to the thickness of the unreinforced section. For many of the studies listed, values of TBR and percentage base course reduction were not directly cited. However, data was presented to allow these calculations to be made. In these cases, data was examined to determine the values listed in Tables 2-8, 2-9, and 2-10.

TBRs ranging from 1 (no measured benefit) to 220[1] have been obtained for test sections containing geotextiles, as illustrated in Table 2-8. Only one study was available that could directly demonstrate a base course savings for test sections containing geotextiles, yielding a figure of 22%. An additional study showed a base course savings of less than 33%; the exact percentage savings was not calculable. For test sections containing geogrids, TBRs ranging from 0.8 (worse performance than test control section) to 670[1], and base course reductions ranging from 30% to greater than 50% were obtained. Test sections containing a geogrid-geotextile composite yielded no information on TBR, while one section produced a base course reduction of 56%. Typical values of TBR for the test sections listed in Table 2-8 for geotextile reinforcement appears to be in the range of 1.5 to 10. For geogrids, a range of 1.5 to 70 appears to be typical.

---

[1]Large TBR values can be measured on significantly over-designed sections, where the defined failure criteria is reached after an extensive number of load cycles.

Table 2-8. Value-Added Benefits for Studies Using Geotextiles

Study	Geotextile Product - Location[1]	AC/Base Thickness (mm)	Subgrade CBR	Rut Depth (mm)	Value-Added Benefits	
					Extension of Life, TBR	Base Course Reduction, BCR (%)
Al-Qadi (lab)	A - B	70/150, and 200	2 - 4	25	1.7 - 3	CTNC[2]
Al-Qadi (lab)	B - B	70/150, and 200	2 - 4	25	1.7 - 3	CTNC
Al-Qadi (field)	A - B	90/100	7	17	1.6	CTNC
Al-Qadi (field)	A - B	90/150	7	17	CTNC	< 33
Anderson	L - B	105/450	NR[2]	NR	CTNC	22
Barksdale	C - B	25/150	2.9	12.5	2.8	CTNC
Barksdale	C - B	38/200	2.7	12.5	1.0	CTNC
Barksdale	C - M	38/200	2.7	12.5	4.7	CTNC
Barksdale	C - M	38/200	3.2	12.5	2.2	CTNC
Brown	G - B	50/150	2 - 8	10 - 25	None	CTNC
Brown	H - B	50/150	2 - 8	10 - 25	None	CTNC
Cancelli (lab)	E - B	75/300	3	25	1.7	CTNC
Cancelli (field)	E - B	75/400	3	10	220	CTNC
Halliday	D - B	160/300	0.7 - 4.3	20	None	CTNC
Humphrey	J - B	180/580	3	NR	NTD[2]	NTD
Humphrey	K - B	180/640	3	NR	NTD	NTD
Perkins	I - B	75/300	1.5	22	8.5	CTNC

Notes: 1. For product code see Table 2-4. Location code is B = Bottom and M = Middle.
2. NR = Not Reported, NTD = None To Date, CTNC = Comparative Test Not Conducted

Table 2-9. Value-Added Benefits for Studies Using Geogrids

Study	Geogrid Product-Location[1]	AC/Base/ Subbase Thickness (mm)	Subgrade CBR	Rut Depth (mm)	Value-Added Benefits	
					Extension of Life, TBR	Base Course Reduction, BCR (%)
Al-Qadi (lab)	B - B	70/150	2 - 4	NR[2]	NR	NR
Al-Qadi (field)	B - B	90/100	7	21	1.4	CTNC[2]
Al-Qadi (field)	B - B	90/150	7	21	CTNC	<33
Barker	B - M[3]	75/150/150	27	25	1.2	CTNC
Barksdale	A - B	38/200	2.5	12.5	1.0	CTNC
Barksdale	A - M	38/200	3.2	12.5	2.8	CTNC
Cancelli (lab)	A - B	75/300	1	25	17	CTNC
Cancelli (lab)	D - B	75/300	3	25	1.7	CTNC
Cancelli (lab)	H - B	75/300	8	25	3.2	CTNC
Cancelli (lab)	H - B	75/300	18	12.5	4.5	CTNC
Cancelli (lab)	H - B	75/300	3	25	5.2	CTNC
Cancelli (lab)	H - B	75/300	1	25	15	CTNC
Cancelli (lab)	H[4]	75/300	1	25	300	CTNC
Cancelli (lab)	H - B	75/300	3	25	CTNC	30
Cancelli (lab)	I - B	75/300	1	25	42	CTNC
Cancelli (lab)	J - B	75/300	3	25	7.1	CTNC
Cancelli (lab)	J - B	75/300	1	25	70	CTNC
Cancelli (field)	A - B	75/300	8	7	1.2	CTNC
Cancelli (field)	A - B	75/500	3	13	8.4	CTNC
Cancelli (field)	A - B	75/300	3	20	220	CTNC
Cancelli (field)	A - B	75/400	3	7	340	CTNC
Cancelli (field)	B - B	75/400	3	5	410	CTNC
Cancelli (field)	B - B	75/1000	1	<15	CTNC	<50
Cancelli (field)	H - B	75/300	8	7	1.6	CTNC
Cancelli (field)	H - B	75/500	3	11	13	CTNC
Cancelli (field)	H - B	75/300	3	14	300	CTNC
Cancelli (field)	H - B	75/400	3	7	330	CTNC

Table 2-9. Value-Added Benefits for Studies Using Geogrids (cont.)

Study	Geogrid Product - Location[1]	AC / Base / Subbase Thickness (mm)	Subgrade CBR	Rut Depth (mm)	Value-Added Benefits	
					Extension of Life, TBR	Base Course Reduction, BCR (%)
Cancelli (field)	K - B	75/400	3	5	410	CTNC[2]
Cancelli (field)	K - B	75/1000	1	< 12	CTNC	> 50
Cancelli (field)	L - B	75/500	3	11	13	CTNC
Cancelli (field)	L - B	75/300	3	17	250	CTNC
Cancelli (field)	L - B	75/400	3	3	670	CTNC
Cancelli (field)	L - B	75/1000	1	< 12	CTNC	> 50
Collin	A - B	50/180-300	1.9	25	2 - 3.3	CTNC
Collin	B - B	50/180-300	1.9	25	2 - 10	CTNC
Haas	A - B	100/200	8	20	3.3	CTNC
Haas	A - M	100/200	8	20	3.1	CTNC
Haas	A - T	100/200	8	20	0.8	CTNC
Haas	A - B	75/200	3.5	20	3.0	CTNC
Haas	A - B	75/200	1	20	1.8	CTNC
Haas	A - B	75/300	0.5	20	0.8	CTNC
Haas	A[4]	75/300	0.5	20	0.8	CTNC
Haas	A - B	75/200	3.5	20	CTNC	50
Humphrey	K - B	180/640	3	NR[2]	NTD[2]	NTD
Huntington	A - M	100/280	4	3	CTNC	35
Kinney	B - B	61/240-355	2.5	20	2 - 34	CTNC
Kinney	M - B	61/203-355	2.5	20	2 - 8.5	CTNC
Miura (lab)	A[4]	50/150/200	NR	5	1.9	CTNC
Miura (lab)	A[5]	50/150/200	NR	5	5.4	CTNC
Miura (lab)	B[6]	50/150/200	NR	5	4.2	CTNC
Miura (lab)	B - B	50/150/200	NR	5	8	CTNC
Miura (lab)	C[6]	50/150/200	NR	5	3	CTNC
Mirua (field)	B - B	50/150/200	NR	NR	NPA[2]	NPA
Mirua (field)	C - B	50/150/200	NR	NR	NPA	NPA

Table 2-9. Value-Added Benefits for Studies Using Geogrids (cont.)

Study	Geogrid Product - Location[1]	AC / Base / Subbase Thickness (mm)	Subgrade CBR	Rut Depth (mm)	Value-Added Benefits	
					Extension of Life, TBR	Base Course Reduction, BCR (%)
Perkins	A - B	75/300	1.5	24	17	CTNC[2]
Perkins	A[7]	75/300	1.5	17	56	CTNC
Perkins	A - B	75/375	1.5	17	17	CTNC
Perkins	B - B	75/300	1.5	16	45	CTNC
Small	B - B	20/40	NR[2]	6	4.3	CTNC
Small	B - M	20/40	NR	6	92	CTNC
Small	B - B	20/40	NR		4 - 92	CTNC
Webster	A - B	50/350	3	25	2.7	CTNC
Webster	B - B	50/450	3	25	1.3	CTNC
Webster	B - M	50/350	3	25	2.2	CTNC
Webster	B - B	50/300	3	25	3.1	CTNC
Webster	B - B	50/350	3	25	4.7	CTNC
Webster	B - B	50/250	8	25	6.7	CTNC
Webster	B - B	50/150	8	25	22	CTNC
Webster	B - B	50/250	8	25	CTNC	40
Webster	D - B	50/350	3	25	1.1	CTNC
Webster	E - B	50/350	3	25	0.9	CTNC
Webster	F - B	50/350	3	25	0.9	CTNC
Webster	G - B	50/350	3	25	1.6	CTNC

Notes:
1. For product code see Table 2-5. Location code is B = Bottom, M = Middle, T = Top.
2. NR = Not Reported, NPA = Not Possible to Analyze, NTD = None To Date, CTNC = Comparative Test Not Conducted.
3. Middle of 150 mm base with 150 mm of subbase below base.
4. Two layers at bottom and middle of base.
5. Two layers at bottom of base and bottom of subbase.
6. Bottom of subbase.
7. 1/3 up in base.

Table 2-10. Value-Added Benefits for Studies Using Geogrid-Geotextile Composites

Study	Composite Product	AC/Base/ Thickness (mm)	Subgrade CBR	Rut Depth (mm)	Value-Added Benefits	
					Extension of Life, TBR	Base Course Reduction, BCR (%)
Anderson	Geogrid A and Geotextile L	105/450	NR[1]	NR	CTNC[1]	56
Humphrey	Geogrid K and Geotextile K	180/640	3	NR	NTD[1]	NTD

Note: 1. NR = Not Reported, NTD = None To Date, CTNC = Comparative Test Not Conducted.

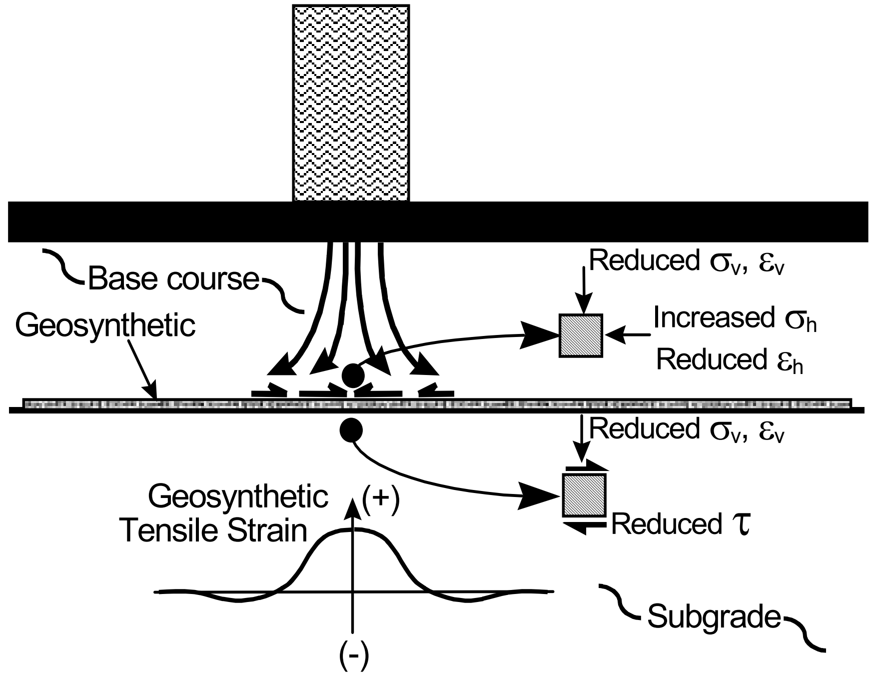
2.4 PAVEMENT REINFORCEMENT MECHANISMS

2.4.1 Base Reinforcement

The purpose of this section is to describe the state-of-knowledge pertaining to the mechanisms by which geosynthetics provide base (or subbase) reinforcement of flexible pavements. Historically, the main reinforcement mechanism attributed to geosynthetics in paved roads is commonly called base course lateral restraint. This mechanism was originally described by Bender and Barenberg (1978) and later elaborated on by Kinney and Barenberg (1982) for geotextile-reinforced unpaved roads. By laterally restraining the soil, four components of reinforcement are potentially achieved, as shown in Figure 2-1. These components include: (i) preventing lateral spreading of the base or subbase aggregate; (ii) increasing confinement and thus the strength of the base or subbase in the vicinity of the reinforcement; (iii) improving vertical stress distribution on the subgrade; and (iv) reducing of shear stress in the subgrade. As a result of these multiple reinforcement components and to avoid the assumption that only the first component is achieved, the lateral restraint mechanism has also been referred to as *shear-resisting interface*, as suggested in Perkins et al. (1998a).

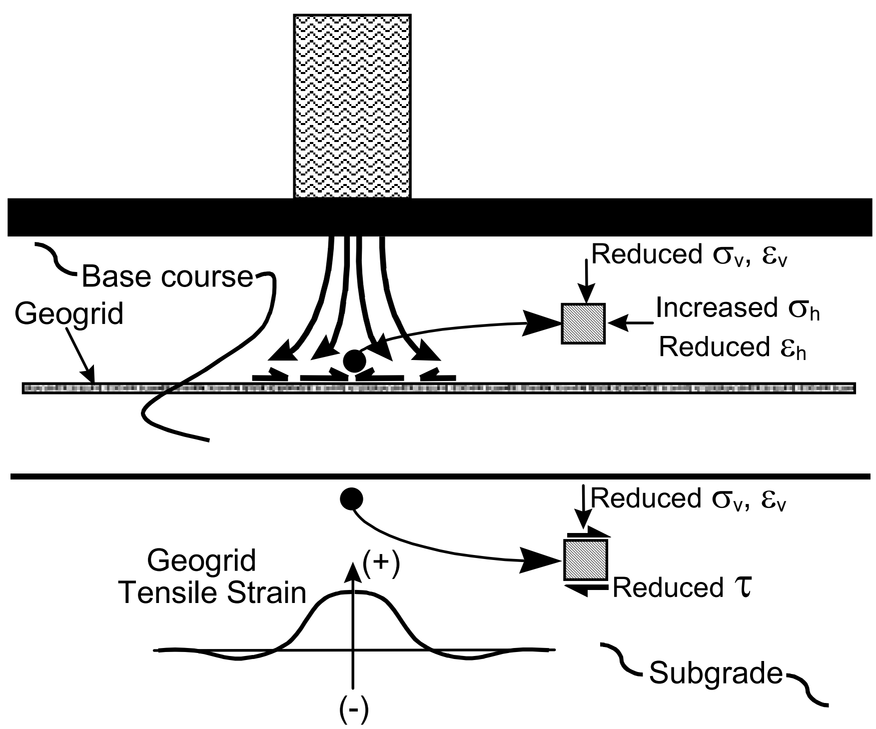
The reinforcement mechanism of a lateral restraint, or shear-resisting interface, develops through shear interaction of the base course layer with the geosynthetic layer (or layers) contained in or at the bottom of the base aggregate (Figure 2-1). Vehicular loads applied to the roadway surface create a lateral spreading motion of the base course aggregate. Tensile lateral strains are created in the base below the applied load as the material moves down and out away from the load. Lateral movement of the base allows for vertical strains to develop, leading to a permanent rut in the wheel path.

Placement of a geosynthetic layer or layers in or at the bottom of the base course allows for shear interaction to develop between the aggregate and the geosynthetic, as the base attempts to spread



a .

Reinforcement at base/subgrade interface.



b. Reinforcement (geogrid) in base course.

Figure 2-1. Illustration of reinforcement mechanisms.

laterally. Shear load is transmitted from the base aggregate to the geosynthetic and places the geosynthetic in tension. The relatively high stiffness of the geosynthetic acts to retard the development of lateral tensile strain in the base adjacent to the geosynthetic. Lower lateral strain in the base results in less vertical deformation of the roadway surface. Hence, the first mechanism of reinforcement corresponds to direct prevention of lateral spreading of the base aggregate.

Shear stress developed between the base course aggregate and the geosynthetic provides an increase in lateral confining stress within the base. Granular materials generally exhibit an increase in elastic modulus with increased confining stress. The second base (or subbase) reinforcement component results from an increase in stiffness of the base (or subbase) course aggregate, when adequate interaction develops between the base (or subbase) and the geosynthetic. The increased stiffness of this layer results in lower vertical strains in the base. An increase in modulus of the base would also be expected to result in lower dynamic, recoverable vertical deformations of the roadway surface, implying that fatigue of the asphalt concrete layer would be reduced. Models of reinforcement relying upon an increase in confinement and modulus of the base include Kinney et al. (1998a) and Sellmeijer (1990).

The presence of a geosynthetic layer in, or at the bottom, of the base can also lead to a change in the state of stress and strain in the subgrade. For layered systems, where a less stiff subgrade material lies beneath the base (or subbase), an increase in modulus of the base (or subbase) layer results in an improved, more broadly distributed vertical stress on the subgrade. In general, the vertical stress in the subbase or subgrade directly beneath the geosynthetic and applied load should decrease as the base (or subbase) layer stiffness increases. The vertical stress on the subgrade will become more widely distributed, meaning that surface deformation will be less and more uniform. Hence, a third reinforcement component results from an improved vertical stress distribution on the subgrade.

The fourth reinforcement component results from a reduction of shear strain in the subgrade soil. It is expected that shear strain transmitted from the base (or subbase) course to the subgrade would decrease as shearing of the base transmits tensile load to the reinforcement. Less shear strain, coupled with less vertical stress results in a less severe state of loading (Houlsby and Jewell, 1990), leading to lower vertical strain in the subgrade.

Prerequisite to realizing the reinforcement components of the shear-resisting interface described above is the development of a strain distribution in the geosynthetic similar to that shown in Figure 2-1. Haas et al. (1988), Miura et al. (1990) and Perkins et al. (1998a,b) presented data demonstrating such trends for paved roadways using geogrid reinforcement, while Perkins (1999b) showed this effect for a geotextile. Haas et al. (1988) and Perkins (1999b) showed reduced vertical stress on the subgrade when reinforcement was present. Perkins (1999b) showed that radial strain in the bottom of the base was reduced by the presence of reinforcement. Perkins (1999b) showed similar results for the top of the subgrade, indicating that shear in the top of the subgrade was reduced by reinforcement.

2.4.2 Subgrade Restraint

The purpose of this section is to describe the state-of-knowledge pertaining to the mechanisms by which geosynthetics provide subgrade restraint reinforcement of pavements. Historically, the use of geosynthetic reinforcement to provide subgrade restraint during construction of flexible or rigid pavements is somewhat commonplace. Subgrade restraint occurs when a geosynthetic is placed at the subgrade/subbase or base interface to increase the support of construction equipment over a weak or soft subgrade. The primary mechanism with this application is increased bearing capacity, although lateral restraint and/or tension membrane effects may also contribute to load-carrying capacity, as illustrated in Figure A-2.

Coincident functions of separation and filtration for construction over wet, saturated conditions must be addressed. A geosynthetic placed at the interface between the aggregate base course and the subgrade functions as a separator to prevent two dissimilar materials (subgrade soils and aggregates) from intermixing. Geotextiles, geogrids, and GG-GT composites perform this function by preventing penetration of the aggregate into the subgrade. Geotextiles, GG-GT composites, and adjacent soils can perform as a filter to prevent intrusion of subgrade soils up into the base course aggregate.

Some projects investigate performance of various geosynthetics over site specific wet, saturated soils with test sections to complete design of construction options. For example, U.S. Army Corps of Engineers (1999) investigated several construction options to minimize excavation of very wet and unstable subgrade soils. Several test strips were built and loaded, and construction traffic rut depths were measured. Construction options were developed on a basis of comparing performance of the various test strips.

2.5 RELATED RESEARCH

Work performed to examine the utility of geosynthetics as reinforcement in unpaved roads began in the mid-1970s. Geotextiles were examined first, since geogrids were not readily available until the mid-1980s. Early applications focused on reinforcement in temporary unpaved roads. Experiments were generally devised to examine roadway rutting behavior subject to relatively heavy loads that were applied for a relatively small number of load applications. As a result, test sections were generally built with the expectation that relatively large rut depths (often in excess of 75 mm) would develop in as few as 100 vehicle passes, which also generally required that vehicles be trafficked in a channeled fashion.

Early studies of temporary roads often described reinforcement in terms of a tensioned-membrane reinforcement mechanism (Steward et al., 1977, Bender and Barenberg, 1978), or an increased subgrade bearing capacity and membrane support (Haliburton and Barron, 1983). These types of reinforcement mechanisms are not appropriate for permanent, paved roads because large rutting is required to mobilize the reinforcement strength. Given the combination of soft subgrades, heavy vehicle loads, and large permissible rut depths, base (or subbase) reinforcement mechanisms pertinent to paved roads were either disregarded or largely masked by a roadway system that was allowed to deform and fail relatively rapidly. In other words, base (or subbase) reinforcement mechanisms pertinent to paved roads rarely had the opportunity to contribute to performance because of the severity of loading and the relatively rapid failure of the roadway system.

As a result of this focus, very little work has been conducted to examine the base (or subbase) reinforcement benefit of geosynthetics for permanent unpaved or lightly surfaced (chip and spray) roads, where limits on rutting are similar to those of flexible paved roads. Several studies suggest that under certain conditions, reinforcement mechanisms pertinent to permanent roads were mobilized during the early stages of loading on a temporary unpaved road. For example, Robnett et al. (1980) showed that the initial rate of rut deformation was reduced by the use of geotextiles with greater tensile modulus values. Milligan and Love (1985) indicated that geogrid-reinforced sections began to show less displacement for a given load starting at a load level approximately equal to 50% of the failure load for the unreinforced sections. Bearden and Labuz (1999) demonstrated that a heavy nonwoven geotextile with an interface friction angle approximately equal to the aggregate performed better in terms of rutting than did a slit film woven geotextile having a lower interface friction angle.

3.0 POTENTIAL GEOSYNTHETIC BENEFITS

3.1 INTRODUCTION

The Federal Highway Administration (FHWA) Geosynthetics Engineering Manual (Holtz et al., 1998) lists four possible functions of geosynthetics in pavements structures: separation, filtration, drainage, and reinforcement. (See Appendix A for applicable excerpt from this manual.) Furthermore, the following benefits of using geosynthetics in roadways are identified:

1. *Reducing the intensity of stress on the subgrade and preventing the base aggregate from penetrating into the subgrade (function: separation).*
2. *Preventing subgrade fines from pumping or otherwise migrating up into the base (function: separation and filtration).*
3. *Preventing contamination of the base materials which may allow more open-graded, free-draining aggregates to be considered in the design (function: filtration).*
4. *Reducing the depth of excavation required for the removal of unsuitable subgrade materials (function: separation and reinforcement).*
5. *Reducing the thickness of aggregate required to stabilize the subgrade (function: separation and reinforcement).*
6. *Reducing disturbance of the subgrade during construction (function: separation and reinforcement).*
7. *Allowing an increase in subgrade strength over time (function: filtration).*
8. *Reducing the differential settlement of the roadway, which helps maintain pavement integrity and uniformity (function: reinforcement). Geosynthetics will also aid in reducing differential settlement in transition areas from cut to fill. {NOTE: Total and consolidation settlements are not reduced by the use of geosynthetic reinforcement.}*
9. *Reducing maintenance and extending the life of the pavement (functions: all).*

The benefits listed in the FHWA manual have been verified both through research and design methods supported by over 30 years of experience. However, an obvious potential geosynthetic benefit that is omitted both from the above list and from the AASHTO M288 specification (see applicable excerpt, Appendix B) is base (or subbase) reinforcement of a roadway to increase the pavement design life or reduce the section thickness. (Reinforcement is mentioned in the AASHTO M288 specifications, but only in the context of extremely soft subgrades (CBR<1), and material properties are not provided, as they are design procedure specific.) The omission of the potential base/subbase reinforcement benefits in the FHWA manual (Holtz et al., 1998) and AASHTO (1997) was due to the absence of information on the following:

- quantifiable verification of the benefit of base and subbase reinforcement;

- the deformation response required to achieve reinforcement, which has historically been assumed to be too high for pavement structures;
- the potential for dynamic creep and stress relaxation in the reinforcement, which could lead to reduction in benefits over the design life of a road;
- cost benefit information to justify the higher cost of higher strength, higher stiffness, higher modulus geosynthetics;
- performance-related material physical properties and geometries needed for design and construction;
- lack of understanding regarding the influence of aggregate sizing and geosynthetic interaction; and
- potentially widely varying behavior using different types of geosynthetics.

Much of the information required to answer these questions now exists or is being developed, as indicated by the literature review in the previous section. When synthesized, the existing research and trial studies provide strong evidence of substantial benefits associated with reinforcing base and subbase layers, under certain conditions. The literature also supports the reinforcement benefits identified in items number 1, 4, 5, 6, 8, and 9 above. In fact, the literature indicates that a reinforcement effect is almost always present, even with (low modulus) nonwoven geotextiles. Multiple benefits are often achieved through a combination of reinforcement with other functions. The primary issue is this: Will the addition of reinforcement be additive or exclusive of the benefits from other functions?

When evaluating the influence and magnitude of the reinforcing effects, numerous variables appear to impact performance. The literature review shows magnitude of pavement performance ranging from no improvement to a multiple order of magnitude increase in design life. A summary of the variables that lead to this performance range is presented in Table 3-1.

However, even with the many variables that may affect pavement performance, several trends in potential benefits of reinforcement emerge when comparing similar studies. A summary of the reinforcement benefits obtained from the literature review, for the conditions listed, is provided in Table 3-2.

Table 3-1. Variables That Influence the Effect of Reinforcement

Pavement Component	Variable	Range from Test Studies/ Remarks	Condition where Reinforcement Appears to Provide Most Benefit
Geosynthetic	Structure	Rigid (extruded) and flexible (knitted and woven) geogrids, woven and nonwoven geotextiles, geogrid-geotextile composites	See Table 4-1 and Table 4-2
	Modulus (@ 2% and/or 5% strain)	100 kN/m to 750 kN/m	Higher modulus improves potential for performance
	Location	Geogrid	Moderate load ($\leq$ 80 kN axle load): Bottom of thin bases ($\leq$ 250 mm), middle for thick (>300 mm) bases Heavy load (> 80kN axle load): Bottom for thin bases ($\leq$ 300 mm), middle for thick bases (>350mm)
		Geotextile	Bottom of base, on the subgrade
		Geogrid-geotextile composite	Bottom of open-graded base OGB
	Surface	Slick versus rough (firmer versus soft)	Rough
	Geogrid Aperture	15 mm to 64 mm	> D_{50} of adjacent base/subbase[1]
	Aperture Stiffness	Rigid to flexible	Rigid
Subgrade Condition	Soil Type	SP, SM, CL, CH, ML, MH, Pt	No relation noted
	Strength	CBR from 0.5 to 27: Note: Low - CBR < 3, Firm to V. Stiff - 3 $\leq$CBR$\leq$ 8, and Firmer - CBR > 8	CBR < 8 (M_R < 80 MPa)
Subbase	Thickness	0 to 300 mm	No subbase
	Particle Angularity	Rounded to angular	Angular
Base	Thickness	40 mm to 640 mm	$\leq$ 250 mm for moderate loads
	Gradation	Well graded to poorly graded	Well graded
	Angularity	Angular to subrounded	Angular
Pavement	Type	Asphalt, concrete, unpaved	Asphalt and unpaved
	Thickness	25 mm to 180 mm	75 mm

Table 3-1. Variables That Influence the Effect of Reinforcement (cont.)

Pavement Component	Variable	Range from Test Studies/ Remarks	Condition where Reinforcement Appears to Provide Most Benefit
Design	Pavement loading	200 kPa to 1800 kPa	Does not perform on significantly under-designed pavements
Construction	Pre-rutting potential	None in lab to pre-rutted in field	Unknown
NOTE: 1. Based upon judgement of authors, not upon summarized research.			

Table 3-2. Reinforcement Benefits

Benefit	General Anticipated Magnitude	Applicability
Reducing Under Cut (i.e., the depth of excavation required for the removal of unsuitable subgrade materials)	Reduced up to 50%	CBR <3 (M_R < 30 MPa)
Reducing the thickness of aggregate required to stabilize the subgrade	Reduced up to 50%	CBR <3 (M_R < 30 MPa)
Reducing disturbance of the subgrade during construction	Allows construction of relatively thin base (subbase)	CBR <3 (M_R < 30 MPa)
Reinforcement of the subbase aggregate in a roadway to reduce the section	Reduced up to 250 mm with 75 mm typical	Depends on depth of base and initial depth of base/subbase
Reinforcement of the base aggregate in a roadway to reduce the section	Reduced up to 150 mm with 75 mm typical (20 to 50%)	Strong potential benefit
Reinforcement of the subbase aggregate in a roadway to increase its design life	TBR = 1 to 3.8	Depends on depth of base and initial depth of base and subbase
Reinforcement of the base aggregate in a roadway to increase its design life	TBR = 1 to 10	Strong potential benefit
Improved reliability	Improves performance during overload and/or seasonally weak subgrade conditions	Always a benefit

3.2 PERMANENT PAVED ROADS

3.2.1 Benefits of Geosynthetic Reinforcement

In evaluating studies on permanent paved roads, it is difficult to develop a definitive relationship between either the section thickness or the corresponding equivalent structural number and the benefits of reinforcement. Several studies indicated an optimum benefit when the geosynthetic was placed at the bottom of a 200-300 mm thick base layer. For thicker base sections, the best location appeared to be in the middle of the base, where geogrids were found to perform best. However, for thin bases (less than 200 mm), separation was noted as an issue for geogrids. Geotextiles or GG-GT composites, in the studies reviewed, tended to perform better for the thin bases, especially where subgrade strengths were below a CBR of 3 (M_R of 30 MPa). The separation issue often masked the reinforcement benefit at low subgrade strengths. Reinforcement benefits were observed with subgrade strengths up to a CBR of 8 (M_R of 80 MPa), and in at least one study some benefit was found at even greater subgrade strengths. However, there does appear to be a relation of decreasing reinforcement benefits with increasing subgrade strength. A qualitative summary of these observed relationships irrespective of the reinforcement type is presented in Table 3-3.

3.2.2 Construction without Geosynthetic Reinforcement

Reinforced pavement sections have several advantages over conventional unreinforced pavement sections. The resilient modulus of unreinforced base and subbase materials tend to be negatively impacted over time by a loss of aggregate to the subgrade and an increase in moisture. By preventing aggregate penetration into the subgrade, the geosynthetic can assist in maintaining the section thickness. Also, mechanical (geosynthetic) reinforcement materials are not significantly affected by the moisture in the base or subbase. Aggregate is also a natural resource that often requires some level of conservation. However, in areas where good quality base and subbase materials are plentiful and relatively inexpensive, and where over-excavation is not required, there may be little (initially apparent) cost benefit in using reinforcement.

Other conventional options include the use of lime, cement, or fly ash stabilization of soft subgrades. These methods tend to be labor intensive and sensitive to the construction environment. While these methods may be cost competitive with geosynthetic reinforcement for some applications, consideration must be given to the physicochemical characteristics of the soil to determine the suitability of these techniques. There is also an associated construction delay for mixing and, in some cases, hydration that must be considered with these selections. In addition, construction quality control becomes an issue for these alternatives. For reconstruction applications, consideration must

Table 3-3. Reinforcement Benefits for Paved Permanent Roads.

BENEFIT	PERMANENT PAVED ROADS SUBGRADE CONDITION		
	Low **CBR < 3** **(M_R < 30 MPa)**	**Moderate** **3 ≤ CBR ≤ 8** **(30 ≤ M_R ≤ 80 MPa)**	**Firmer** **CBR > 8** **(M_R > 80 MPa)**
Reducing undercut	●	◗	❍
Reducing the thickness of aggregate required to stabilize the subgrade	●	◗	❍
Reducing disturbance of the subgrade during construction	●	◗	❍
Reinforcement of the subbase aggregate in a roadway to reduce the section	●	◗	❍
Reinforcement of the base aggregate in a roadway to reduce the section	◗	●	◗
Reinforcement of the subbase aggregate in a roadway to increase the design life of the pavement	◗	◗	◗
Reinforcement of the base aggregate in a roadway to increase the design life of the pavement	●	●	◗
KEY: ● — usually a benefit ◗ — a known benefit in certain (various) conditions ❍ — usually not a benefit			

also be given to the influence of construction traffic and typical reconstruction project space limitations before selecting one of these alternatives (Laguros and Miller, 1997).

Stabilization of soft subgrade soils using a geotextile that functions as both a separator and a filter (as covered by AASHTO M288) also provides a means to reduce undercut — the thickness of aggregate required to stabilize the subgrade and minimize disturbance of the subgrade during construction. However, no additional structural support is assumed for the inclusion of the geosynthetic. (It should be noted that current research does show foundation support improvements over time, providing a significant potential for increased design life with this application (Black and Holtz, 1997). Also, AASHTO M288 does not cover extremely poor subgrade conditions (CBR < 1) where reinforcement may be required to support the roadway embankment, not just the construction equipment loads, as is assumed for stabilization. In addition to stabilization, AASHTO

M288 addresses the geotextile separation application. The benefits of this application are long-term in that the section thickness is maintained without aggregate contamination over the life of the roadway. Based on the work by Al-Qadi et al. (1994), TBR estimates range from 1.2 to 2.0, depending on the axle load, pavement thickness, subgrade material, base material, and subgrade moisture. While there is no reduction in structural section generally allowed for the separation application, there may be a load-carrying contribution in the form of improved drainage.

Geotextile separators act to maintain permeability of the base materials over the life of the section, and they allow the use of more open-graded, free-draining base and subbase materials. Designers can take advantage of improved drainage quality through associated increases in drainage modifiers used in the AASHTO 1993 design method to quantify the drainage capacity of base course and subbase layers. In high rainfall areas, improved drainage results in as much as a 50% reduction in base course aggregate thickness. The separation application is generally limited to subgrades containing fine-grained soils.

3.3 OTHER APPLICATIONS

As with permanent paved roads, geosynthetics have proven benefits in the construction of temporary paved roads, permanent unpaved roads, and temporary unpaved roads. For unpaved roads, a relationship appears to exist between benefit and section thickness. The effectiveness of base reinforcement appears to decrease with increasing thickness. The greatest benefit appears where the base thickness is less than 300 mm. Maximum benefit occurs when the depth of the reinforcement is within ½ to 1 times the width of the wheel load. Subgrade restraint is applicable to thicker aggregate layers. As with permanent paved roads, the influence of reinforcement decreases with increasing subgrade strength. A qualitative summary of reinforcement benefits for other applications is presented in Table 3-4.

As discussed in Section 3.2.2 for permanent roads, geosynthetic reinforcement presents several advantages over alternative methods, such as increased aggregate thickness and chemical stabilization. Filtration should always provided, if not naturally then with a geotextile filter, for reinforcement over soft clayey or silty subgrades. A geotextile separator or a geotextile for stabilization (see AASHTO M288) are also alternatives to geosynthetic reinforcement, when constructing over soft clayey or silty subgrades.

Table 3-4. Reinforcement Benefits for Other Applications

BENEFIT	**SUBGRADE CONDITION**								
	Low CBR < 3			**Moderate 3≤ CBR ≤ 8**			**Firmer CBR > 8**		
APPLICATIONS	**PT**	**UP**	**UT**	**PT**	**UP**	**UT**	**PT**	**UP**	**UT**
Reducing undercut	●	●	●	◗	❍	❍	❍	❍	❍
Reducing the thickness of aggregate required to stabilize the subgrade	●	●	●	◗	❍	❍	❍	❍	❍
Reducing disturbance of the subgrade during construction	●	●	●	◗	◗	◗	❍	❍	❍
Reinforcement of the subbase aggregate in a roadway to reduce the section	●	●	●	◗	◗	◗	❍	❍	❍
Reinforcement of the base aggregate in a roadway to reduce the section	◗	●	●	◗	◗	◗	◗	◗	◗
Reinforcement of the subbase aggregate in a roadway to reduce rutting and improve trafficability	◗	●	●	◗	❍	❍	◗	❍	❍
Reinforcement of the base aggregate in a roadway to reduce rutting and improve trafficability	◗	●	●	◗	❍	❍	◗	❍	❍

Key: ● = usually a benefit
◗ = a known benefit in certain conditions
❍ = usually not a benefit
PT = Paved Temporary
UP = Unpaved Permanent
UT = Unpaved Temporary

4.0 APPLICABILITY OF GEOSYNTHETIC REINFORCEMENT

4.1 INTRODUCTION

Geosynthetic reinforcement provides benefit to permanent roads both during construction and over the life of the pavement. Geosynthetic reinforcement also provides benefit to temporary roads such as detours, haul and access roads, construction platforms, and stabilized working *tables* required for the construction of permanent roads, as well as embankments over soft foundations.

Geosynthetics allow construction equipment access to sites where the soils are normally too weak to support the initial construction work. This is one of the more typical uses of geosynthetics. Even if the finished roadway can be supported by the subgrade, it may be virtually impossible to begin construction of the embankment or roadway. Such sites require stabilization by dewatering, demucking, excavation and replacement with select granular materials, utilization of stabilization aggregate, chemical stabilization, etc. Geosynthetics, in conjunction with a granular fill, can often be a cost-effective alternative to expensive foundation treatment procedures.

Furthermore, geosynthetics may make it easier for contractors to meet minimum compaction specifications, especially for the first lift(s) over weak subgrades. Over the long-term, a geosynthetic acts to maintain the roadway design section and the base course material integrity. Thus, the geosynthetic will ultimately increase the life of the roadway, whether temporary or permanent.

4.2 PAVED PERMANENT ROADS

Permanent road design essentially consists of selecting structural elements (the pavement surface, base, and subbase) that will reduce the stress of accumulated live loads on the subgrade such that anticipated traffic will be supported over the anticipated design life of the system. If any of the components should fail prematurely, the design life will not be achieved. Yoder and Witczak (1975) defined two types of pavement distress, or failure. The first is a structural failure, in which a collapse of the entire structure, or a breakdown of one or more of the pavement components, renders the pavement incapable of sustaining the loads imposed on its surface. The second type of failure is a functional failure; it occurs when the pavement, due to its roughness, is unable to carry out its intended function without causing discomfort to drivers or passengers or imposing high stresses to vehicles. The cause of these failure conditions may be due to excessive loads, climatic and environmental conditions, poor drainage leading to poor subgrade conditions, and disintegration of the component materials. Excessive loads, excessive repetition of loads, and high tire pressures can cause either structural or functional failures. Properly designed, geosynthetic reinforcements can enhance pavement performance and reduce the likelihood of failures. Reinforcement can also be used to increase the safety factor of minimal designs to account for ESALs greater than design EASLs, occasional overloads, seasonally weak subgrade conditions, and areas of subgrade strengths lower than the design strength.

Of course there are limitations to the application of reinforcement in pavements. The limitations, as well as the optimum use, are related to the pavement type, section and thickness, and the subgrade strength, as indicated in Table 3-1. Very few studies provide comparison of the full range of geogrids (e.g., knitted or woven and extruded with different modulus values, stiffness and aperture sizes) and geotextiles (e.g., heat bonded and needlepunched nonwovens of various weights and mono-filament, slit-film, fibrillated, multiple, and composite filament woven geotextiles of various modulus values). The selection of the most suitable type of geosynthetic reinforcement will also depend on the specifics of the application. For example, some studies found that separation and filtration are important considerations for thin bases [not normally recommended for paved permanent roadways] on weak or seasonally weak subgrades and for unpaved road subgrades susceptible to pumping (e.g., Fannin and Sigurdsson, 1996; Austin and Coleman, 1993). One study found similar results for paved roads (Al-Qadi et al., 1994). Geotextiles or GG-GT composites, bonded or unbonded, are often used for these conditions.

Geogrids are suitable for cohesive and noncohesive subgrades. However, a geotextile should be used with a geogrid (unbonded composite), or a GG-GT composite should be used if a geotextile is required for filtration between the subgrade and base or subbase materials. Also, extruded geogrids are considered to be the optimum geosynthetic material when reinforcement is placed up in the base course aggregate, based upon research to date. A qualitative summary of potential geosynthetic reinforcement applications in relation to project conditions and geosynthetic type is provided in Table 4-1. This summary is based upon research to date, and is subject to change as additional research is completed and experience is gained.

Table 4-1. Qualitative Review of Reinforcement Application Potential for Paved Permanent Roads

Roadway Design Conditions		**Geosynthetic Type**					
Subgrade	**Base/Subbase Thickness [1] (mm)**	**Geotextile**		**Geogrid [2]**		**GG-GT Composite**	
		Nonwoven	**Woven**	**Extruded**	**Knitted or Woven**	**Open-graded Base [3]**	**Well Graded Base**
Low (CBR < 3) (M_R <30 MPa)	150 - 300	❹	●	●	❑	●	⑤
	> 300	❹	❹	◗	◗	◗	⑤
Firm to Very Stiff (3≤ CBR≤ 8) (30≤ M_R ≤ 80)	150 - 300	⑥	◗	●	❑	●	⑤
	> 300	⑥	⑥	◗[7]	❑	❑	⑤
Firmer (CBR > 8) (M_R >80 MPa)	150 - 300	❍	❍	◗	❑	❑	⑤
	> 300	❍	❍	❍	❍	❍	⑤

Key: ● — usually applicable; ◗ — applicable for some (various) conditions; ❍ — usually not applicable; ❑ — insufficient information at this time; ⑤ — see note

Notes:
1. Total base or subbase thickness with geosynthetic reinforcement. Reinforcement may be placed at bottom of base or subbase, or within base for thicker (usually > 300 mm) thicknesses. Thicknesses less than 150 mm not recommended for construction over soft subgrade. Placement of less than 150 mm over a geosynthetic not recommended.
2. For open-graded base or thin bases over wet, fine-grained subgrades, a separation geotextile should be considered with geogrid reinforcement.
3. Potential assumes base placed directly on subgrade. A subbase also may provide filtration.

❹ Reinforcement usually applicable, but typically addressed as a subgrade stabilization application.

⑤ Geotextile component of composite likely is not required for filtration with a well graded base course; therefore, composite reinforcement usually not applicable.

⑥ Separation and filtration application; reinforcement usually not applicable.

7. Usually applicable when placed up in the base course aggregate. Usually not applicable when placed at the bottom of the base course aggregate.

4.3 OTHER APPLICATIONS

Geosynthetic reinforcement may be designed to decrease the base thickness in temporary paved or unpaved roads and in permanent unpaved roads. For unpaved temporary roads where substantial rutting can be tolerated, in addition to lateral restraint of the base/subbase materials, geosynthetic reinforcement provides membrane support for the wheel loads, thus reducing the vertical stress on the subgrade and allowing even further reduction in design requirements. This combined reinforcement application has been recognized in several design methods, as reviewed in Section 5.

For temporary paved roads, such as detours, reinforcement can be used to increase the factor of safety of a minimal thickness design to account for occasional overloads, minimize rutting, and maintain trafficability during the short design life of the section.

Also, for extremely weak subgrades (i.e., CBR<1, shear strength of less than 30 kPa), reinforcement is likely to be required to support the roadway embankment (dead load), not just the wheel loads (live load). In such cases, the weight of the soil in the embankment may exceed the bearing capacity of the foundation soil. For roadways where stability of the embankment foundation is questionable, properly designed high-strength geotextiles or geogrids can provide reinforcement to prevent local shear failure and increase embankment stability. Geosynthetic reinforcement will also reduce embankment displacement during construction and provide more uniform support for the roadway. Design of reinforcement for this application is covered in detail in the FHWA Geosynthetics Engineering Manual (Holtz et al., 1998).

A qualitative summary of the potential applications of geosynthetic reinforcement in relation to the project conditions and geosynthetic type is provided in Table 4-2. This summary is based upon research to date, and is subject to updating as additional research is completed and experience is gained.

Table 4-2. Qualitative Review of Reinforcement Application Potential for Other Roads

Roadway Design Conditions			**Geosynthetic Type**					
Roadway Section	**Subgrade**	**Base/ Subbase Thickness [1] (mm)**	**Geotextile**		**Geogrid [2]**		**GG-GT Composite**	
			Non-woven	**Woven**	**Ex-truded**	**Knitted or Woven**	**Open-graded Base[3]**	**Well Graded Base**
Temporary Unpaved	Low (CBR < 3)	150 - 300	❹	●	●	●	●	⑤
		> 300	❹	❹	◗	◗	◗	⑤
	Moderate (3≤ CBR ≤8)	150 - 300	❍	◗	◗	◗	❍	⑤
		> 300	❍	❍	◗	❑	❍	⑤
	Firmer (CBR > 8)	150 - 300	❍	❍	❍	❍	❍	⑤
		> 300	❍	❍	❍	❍	❍	⑤
Permanent Unpaved	Low (CBR < 3)	150 - 300	❹	●	●	●	●	⑤
		> 300	❹	❹	◗	◗	◗	⑤
	Moderate (3≤ CBR ≤8)	150 - 300	❍	●	●	◗	●	⑤
		> 300	❍	◗	◗	❑	◗	⑤
	Firmer (CBR > 8)	150 - 300	❍	❍	❍	❍	❍	⑤
		> 300	❍	❍	❍	❍	❍	⑤
Temporary Paved	Low (CBR < 3)	150 - 300	❹	●	●	●	●	⑤
		> 300	❹	❹	◗	◗	◗	⑤
	Moderate (3≤ CBR ≤8)	150 - 300	❍	◗	●	◗	●	⑤
		> 300	❍	◗	◗	❑	◗	⑤
	Firmer (CBR > 8)	150 - 300	❍	❍	❍	❍	❍	⑤
		> 300	❍	❍	❍	❍	❍	⑤

Key: ● — usually applicable ◗ — sometimes applicable ❍ — usually not applicable
❑ — insufficient information at this time ⑤ — see note

Notes:
1. Total thickness with geosynthetic reinforcement. Thicknesses less than 150 mm not recommended for construction over soft subgrade. Placement of less than 150 mm over a geosynthetic not recommended.
2. For open-graded base or thin bases over wet, fine-grained subgrades without a subbase filter, a geotextile filter should be considered with geogrid reinforcement.
3. Potential assumes base placed directly on subgrade. A subbase also may provide filtration.

❹ Reinforcement usually applicable, but typically addressed as a subgrade stabilization application.

⑤ Geotextile component of composite likely is not required for filtration with a well graded base course; therefore, composite reinforcement usually not applicable.

[BLANK]

5.0 SUMMARY OF AVAILABLE DESIGN APPROACHES AND PROCEDURES

5.1 BACKGROUND

Proposed design methods for geosynthetic reinforcement in pavement sections are either based on empirical and analytical considerations or analytical models modified by experimental data. To date, a general analytical design solution has not been found that addresses all of the many variables that impact performance and, as a result, that has been validated by experimental data (Perkins and Ismeik, 1997). All empirical design methods are limited by the conditions associated with the experiments of the study. Several methods are based on obtaining a performance level (TBR or BCR) from a laboratory model test. The lab test results must be extrapolated to field conditions for application to design. For a given set of conditions, many of the methods appear to produce reliable results.

5.2 PAVED PERMANENT ROAD DESIGN

Geosynthetics are incorporated into permanent paved road designs for two reasons:

- to reinforce the base and/or subbase; or
- to provide subgrade restraint for construction of the road over weak subgrade conditions.

These applications are covered separately in the following sections.

5.2.1 Base/Subbase Reinforcement

Paved permanent roadway design methods incorporating base/subbase reinforcement generally allow the user to evaluate a reduction in base course thickness or an increase in design life of a section containing a layer of geosynthetic reinforcement. Some methods have been based on the use of specific proprietary geosynthetics, others have been established for generic types of reinforcement, and some have been generically established for any type of geosynthetic reinforcement. Usually, AASHTO pavement design methods are followed; however, some have used the older form of the 1981 AASHTO procedure, while others use the current 1993 form. Design is usually based on the number of ESALs anticipated to reach a specific rut depth in the pavement, the number of ESALs anticipated to reach an equivalent rut depth condition in an unreinforced section, or a modified structural number. Some procedures use a modifying index for determining the structural number. Design procedures are usually available in chart format, and some computer programs have been developed. Summaries of the available design methods for base/subbase reinforcement, along with the basis for their development, are provided in Table 5-1. A discussion of many of these methods — including the constitutive assumptions used in the finite element model studies — is contained in Perkins and Ismeik (1997b).

5.2.2 Subgrade Restraint

Several design methods also exist for the use of reinforcement geosynthetics in subgrade restraint (or stabilization) for permanent road construction. Since some rutting is allowed for the initial lift in constructing these sections, these design techniques mainly rely on the tensioned membrane approach and bearing capacity theory to analyze the reinforcing requirements for these sections. The two most widely used procedures are the Steward et al. (1977) procedure and the Giroud and Noiray (1981) procedure. These methods, along with several variations as provided by geosynthetic manufactures, are summarized in Table 5-2.

The Steward et al. procedure was developed from an earlier method by Barenberg et al., 1975. Based on lab tests and supported by bearing capacity theory, Barenberg and his colleagues proposed that the bearing capacity factor, N_c, (to prevent significant permanent deformation under a small amount of traffic) increased from 3.3 to 6.0 when using a geosynthetic. Based on field tests, Steward et al. (1977) extended this approach for U.S. Forest Service unpaved roads to cover situations where very little rutting was tolerable under high traffic levels (>1000 ESALs) by including an N_c of 2.8 without a geotextile and 5.0 with a geotextile. With these extended factors, both traffic and rut depth could be considered for a variety of wheel loading conditions. The approach was later adopted by the Federal Highway Administration for both temporary roads and the construction platform for permanent roads (Christopher and Holtz, 1985) and is still in use by the FHWA today (Holtz, et al., 1998).

In 1980, Barenberg broadened his earlier method to include the modulus of the geosynthetic based on the deformed shape of the rut in relation to its depth. The support provided by the geosynthetic and the associated reduction in bearing stress could then be calculated for a given rut depth. Giroud and Noiray (1981) proposed a similar design solution based on the deformed shape of the geosynthetic in the rut. The deformed shape was modeled assuming a load spread angle that was also influenced by lateral restraint of the base course. In addition, their method included the effect of traffic passes to generate a design rut depth. Design charts initially developed by Giroud and Noiray covered only the cases for very significant rutting. The charts were later expanded to include a range of rutting conditions by Holtz and Sivakugan (1987).

Table 5-1. Design Approaches and Procedures for Base/subbase Reinforcement

Developer/ Organization	Geosyn-thetic Type[1]	Applicability	Design Method and Basis	Geosynthetic Reinforcement Modification[1]	Distress Mode	Design Format	Empirical Support	Maximum Range of Improvement
Mirafi, 1982	Specific geotextile	$1 \leq CBR \leq 6$	Empirical/ modified AASHTO '72	Layer coefficient ratio equal to reinforced to un-reinforced layer coefficients	N/A	Equations and charts	Field results	7% to 18% reduction in base thickness
Penner et al., 1985	Specific geogrid	Based on $4.3 \leq CBR \leq 5.7$	Empirical/ modified AASHTO '81	SN modifier based on unreinforced to reinforced base layer thickness - reinforcement in middle for base thickness > 250 mm	20 mm rut depth	Equations and charts	Lab test (with load correction factor of 3.5 to 10)	30% to 50% reduction in base thickness
Burd and Houlsby, 1986	Generic geosynthetic	Isotropic, elastoplastic	FEM	Isotropic, linear elastic model using membrane element	surface deforma-tion	FEM computer program	none	Improvement after 4 mm surface deformation
Barksdale et al., 1989	Generic geosynthetic	Isotropic, non-linear elastic	FEM	Linear elastic model using membrane element	surface deforma-tion	FEM computer program	Field results	4% to 18% reduction in base thickness
Burd and Brocklehurst, 1990	Generic geosynthetic	Isotropic, elastoplastic	FEM	Isotropic, linear elastic model using membrane element	surface deforma-tion	FEM computer program	none	Improvement after 12 mm to 25 mm surface deformation
Davies and Bridle, 1990	Generic geosynthetic	Any subgrade with subgrade strain energy used in analysis	Analytical/ calculation of number of load cycles for specific rut depth	Increase in potential energy of the base layer	rut depth	Equations	Verification through comparison with single set of field results	N/A
Miura et al, 1990	Generic geosynthetic	Isotropic, linear elastic	FEM	Isotropic, linear elastic model using truss element	surface deforma-tion	FEM computer program	Field results	5% reduction in vertical deformation
Sellmeijer, 1990	Generic geosynthetic	N/A	Analytical/ elastic-plastic model	Membrane action and lateral restraint using simple law of friction	N/A	Equations	Not compared to experimental results	N/A

Table 5-1. Design Approaches and Procedures for Base/subbase Reinforcement (cont.)

Developer/ Organization	Geosyn-thetic Type[1]	Applicability	Design Method and Basis	Geosynthetic Reinforcement Modification[1]	Distress Mode	Design Format	Empirical Support	Maximum Range of Improvement
Webster, 1993	Specific geogrid	3 ≤ CBR ≤ 8	Empirical/ mod. AASHTO (FAA, 1978)	Direct extrapolation from field test results	Rut depth (25 mm)	Design charts	Field tests	BCR = 5% to 45%
Dondi, 1994	Generic geosynthetic	Isotropic, elastoplastic	FEM	Isotropic, linear elastic model using membrane element	Fatigue, surface deforma-tion	FEM computer program ABAQUS	None	15 to 20% reduction in vertical deformation, TBR = 2 to 2.5
Tensar, 1996	Specific geogrid	1.9≤ CBR ≤ 8	Empirical/ modified AASHTO 93	Life extension and base course reduction from empirically determined TBR	20 mm to 30 mm rut depth	Equations, charts, computer program	Lab (Haas, 1985) & test tracks (Collin, et al., 1996; Webster, 1992) correlated to field tests	TBRs = 1.5 to 10
Wathugala et al., 1996	Generic geogrid	Isotropic, elastoplastic	FEM	Linear elastoplastic von Mises model using solid continuum element	Surface deforma-tion	FEM computer program ABAQUS	None	20% reduction in vertical deformation
Akzo-Nobel, 1998 (now Colbond)	Specific GG-GT composite	Not stated	German road design	Increase in bearing capacity of the unsurfaced road	Bearing capacity	Equations and charts	Plate load tests (Meyer & Elias, 1999)	BCR = 32% to 56%
		1.5 ≤ CBR ≤ 4.5	Design life extension per FEM analysis	Retards development of crack in pavement	Crack in pave-ment	Charts	None available	TBR = 1.1 to 1.3
Zhao and Foxworthy, 1999	Specific geogrid	CBR ≤ 18	Empirical/ modified AASHTO 93	Layer coefficient ratio LCR equal to reinforced to un-reinforced layer coefficients	Rut depth	Equations and spread sheet	Cyclic plate load test and test tracks	Not specifically stated

Note: 1. TBR and adjustment values are usually geosynthetic product-specific. User must verify applicability of empirically derived values to their project conditions. Use of DARWIN, or similar program facilitates life-cycle cost analysis.

5.3 DESIGN OF OTHER APPLICATIONS

The stabilization design methods used for permanent roads are also used for design of temporary unpaved and paved roads. The design method by Giroud and Noiray (1981) shows that the reinforcing function becomes increasingly more important to maintain stability where deep ruts (> 100 mm) can occur, such as for large live loads on thin initial lifts or on thicker sections over softer subgrades. However, for thin roadway sections with relatively small live loads where ruts of less than 100 mm may occur, the separation function is important.

5.4 DESIGN OF GEOSYNTHETIC SEPARATION, FILTRATION, AND DRAINAGE LAYERS

Regardless of which method is used, an assessment of separation, filtration, and drainage requirements should be made. Holtz, et al. (1998) provides guidelines for this assessment. If a geogrid is used and where subgrade conditions require such, the pavement layer adjacent to the subgrade (i.e., either the base or subbase material) should be sufficiently graded to provide subgrade filtration and prevent soil intrusion. Otherwise, the benefit of the geogrid reinforcement can be offset by the subgrade intrusion. For more open bases where a filter is required between the subgrade and base or subbase layers, a geotextile filter with the geogrid (unbonded composite) or a GG-GT composite should be used. If geotextiles are used as the reinforcement, or are to be used in conjunction with a geogrid as a filter, the minimum properties of geotextiles required to survive various levels of construction stresses and to provide separation and/or filtration can be found in AASHTO M288-96 (see Appendix B).

At least one method incorporates geotextiles as separators into permanent road design (Al-Qadi et al., 1997 and Amoco, 1999). This method takes advantage of the use of a separator in maintaining the quality of the base/subbase over the design life and the ability to use more open-graded base/subbase aggregate with geotextile separators to improve drainage. The method allows for an evaluation of design life improvement through modified estimates of ESALs, based on correlations with measured TBR values from both laboratory and field tests. Furthermore, the use of free-draining, open-graded base in conjunction with geotextile separators to improve drainage modifiers can lead to a reduction in the required structural section. In high rainfall areas, improved drainage by using permeable base instead of poorly draining dense graded base could result in a 50% reduction in base course aggregate.

Table 5-2. Design Approaches and Procedures for Subgrade Restraint/Stabilization and Separation in Permanent Roads

Developer/ Organization	Geosyn-thetic Type	Range of Subgrade Strength	Design Method and Basis	Geosynthetic Reinforcement Modification	Distress Mode	Design Format	Empirical Support	Maximum Range of Improvement
FHWA Geosynthetics Manual (Holtz et al., 1998)	All	CBR ≤ 3	Stewart et al., 1977/ bearing capacity theory (see Section 5.2)	Stabilization (i.e., separation and filtration, and sometimes reinforcement) extended to permanent roads	25 mm to 150 mm rutting of initial lift	Charts	Field data	30% to 40% reduction of stabilization lift
Mirafi	Specific geotextile	N/A	Barenburg, 1980	N/A	Bearing failure	Equations	N/A	50% reduction
Tensar, 1986	Specific geogrid	CBR ≤ 3	Modified Stewart et al., 1977/bearing capacity theory	Stabilization - geogrid + gravel to provide equivalent CBR for permanent road design	Not defined	Charts and equations, computer program	Field results	30% to 40% reduction of stabilization lift
Tenax, 1996	Specific geogrid	CBR ≤ 4	Giroud and Noiray, 1981 (see Section 5.2) and Giroud et al. 1985	Mobilized reinforcements strength a function of rut depth and geosynthetic tensile modulus	Rut depth	Equations and computer program	N/A	
Al-Qadi et al., 1997	Generic geotextile	CBR ≤ 7	Empirical/ modified AASHTO '93	Separation - modified ESALs based on TBR value	Rut depth of 25 mm	Charts and computer program	Lab correlated to field test - correction factor of 5 to 12.5	20% to 100% improvement in design life of pavement
Synthetic Industries, 1997	Specific geotextile	CBR ≤ 3 (CBR > 3 - separation only)	FHWA Geotextile Manual (1985 & 1995)	Stabilization (i.e., separation and filtration, and sometimes reinforcement)	25 mm to 150 mm rutting of initial lift	Charts	Field results	30% to 40% reduction of stabilization lift
AKZO, 1998 (currently Colbond)	Specific geogrid	CBR ≤ 4.5	Giroud and Noiray (see Section 5.2)	Stabilization - geogrid + gravel to provide modified bearing capacity for permanent road design	75mm to 200 mm rutting of initial lift	Charts and equations	Field data	30% - 50% reduction in stabilization lift

Table 5-2. Design Approaches and Procedures for Subgrade Restraint/Stabilization and Separation in Permanent Roads (cont.)

Developer/ Organization	Geosyn-thetic Type	Range of Subgrade Strength	Design Method and Basis	Geosynthetic Reinforcement Modification	Distress Mode	Design Format	Empirical Support	Maximum Range of Improvement
Amoco, 1999	Specific geotextile	CBR ≤ 7	Empirical/ modified AASHTO '93	Separation - modified ESALs based on TBR value, use of AASHTO drainage modifiers	Rut depth of 25 mm	Charts, equations, software	Lab correlated to field results	20% to 100% improvement in pavement life
Huesker	Specific geogrid	CBR ≤ 3	Giroud and Noiray (see Section 5.2)	Stabilization and reinforcement	75 mm to 300 mm rutting of initial lift	Charts and equations	Field results	30% - 50% reduction in stabilization lift

[BLANK]

6.0 VALUE-ADDED COST BENEFITS

6.1 BACKGROUND

There are many benefits to reinforcement of permanent pavements with geosynthetics, as discussed in Section 3. Cost savings benefits should be quantified using life-cycle costs. As stated in the AASHTO Design of Pavement Structures (1993):

> *It is essential in economic evaluation that all costs occurring during the life of the facility be included. When making economic comparisons this has not always been carefully practiced or even understood by pavement designers because comparisons were often made over a fixed, equal design period. Thus, designers assumed that first-cost comparisons were adequate for economic studies. This is not true, and, in order to emphasize the need for a complete cost analysis, the term "life-cycle costs" was coined about 1970 for use with pavements.*
>
> *Life-cycle costs refer to all costs (and, in the complete sense, all benefits) which are involved in the provision of a pavement during its complete life cycle. These include, of course, construction costs, maintenance costs, rehabilitation costs, etc. . . .*
>
> *. . . .*
>
> *"Life-cycle costs" then is a term coined to call special attention to the fact that a complete and current economic analysis is needed if alternatives are to be truly and correctly compared to each other.*

It is recommended that an economic evaluation of a proposed reinforced pavement project be performed with life-cycle cost analysis. However, solely examining initial construction costs may demonstrate a cost savings with a geosynthetic reinforcement. In this case, a detailed life-cycle cost analysis may not be required unless total savings over the project life must be quantified (e.g., to compare the savings in thickness reduction as compared to maintaining the thickness and increasing the design life). The initial cost approach oversimplifies the evaluation. Life-cycle cost will invariably show a greater cost savings and is recommended if the initial cost approach does not appear to show a sufficient economic advantage for using reinforcement.

Initial construction cost savings are examined in Section 6.2. The outlined procedures typically will result in demonstration of a cost savings for construction over low subgrade conditions. Cost savings also may be computed in terms of base thickness reduction for some moderate subgrade conditions. A case history documentation of initial construction cost savings is presented in Section 6.3. However, maintaining the thickness and extending the design life may provide an even greater cost savings. Life-cycle cost analyses are examined in Section 6.4. As previously indicated, life-cycle costs should be examined when the simplistic approach of initial construction costs do not show a savings with use of geosynthetic reinforcement. An example life-cycle cost analysis is summarized in Section 6.5. Other benefits, which cannot be quantified as a cost savings, should be factored into the decision-making process. These potential benefits are reviewed under Section 6.6.

6.2 INITIAL CONSTRUCTION COSTS

Initial construction cost savings are usually realized when constructing over a low subgrade. The amount of calculated savings may vary with the method and/or geosynthetic used in design. However, the approach to quantifying the cost savings is independent of the design method and geosynthetic. A step-by-step procedure for computing an initial construction cost savings follows. This procedure assumes that the preferred design procedure has already been selected.

STEP 1. Quantify costs.

A. Base course material in-place ($BC), $/mm/sq. m (dollars/millimeter thickness/square meter of pavement)
B. Over-excavation removal and disposal ($OE), $/mm/sq. m
C. Geosynthetic in-place ($G), $/sq. m

STEP 2. Quantify base course and over-excavation thickness reductions with geosynthetic.

Thickness reduction, Δt_r, from the selected design procedure.

STEP 3. Compute initial construction cost savings (or increase).

A. Compute construction cost savings ($CCS) per square meter of pavement area.

$$\Delta t_r \text{ (\$BC + \$OE) - \$G = \$CCS \$/sq. m}$$

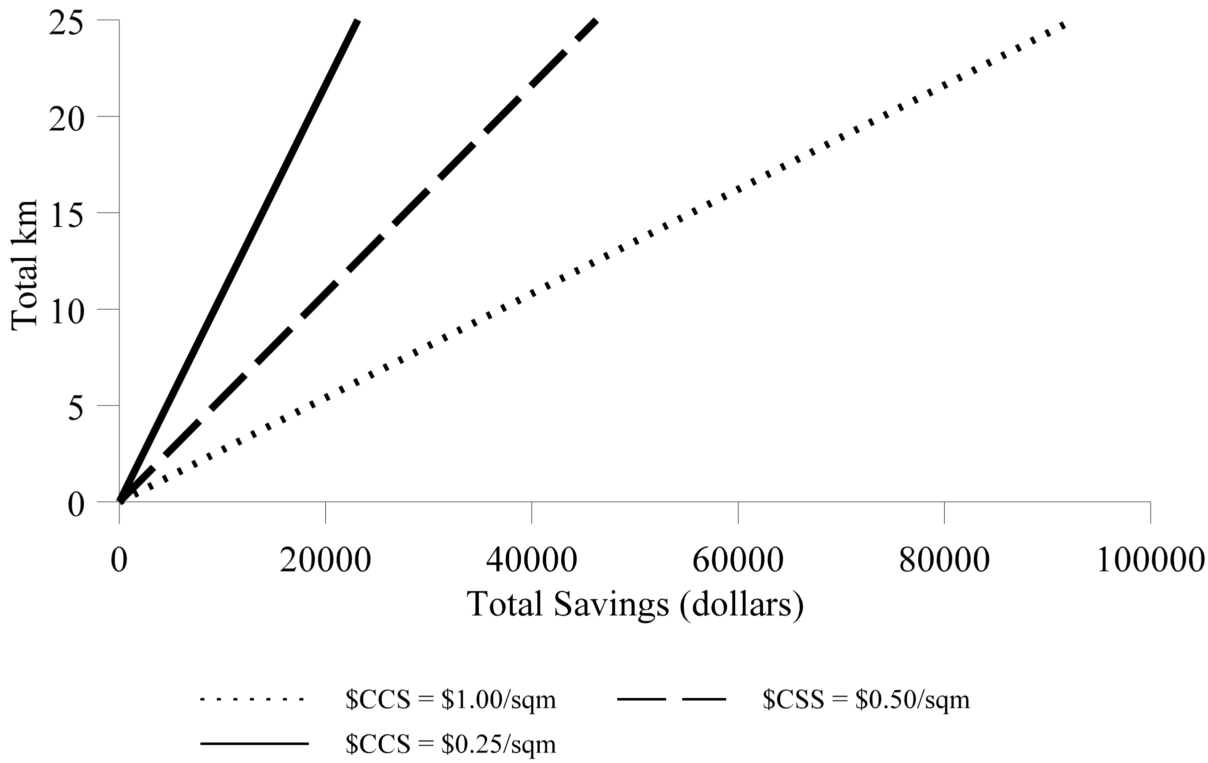


Figure 6-1. Initial construction cost savings.

B. Compute cost savings on a lane-kilometer basis. Use Figure 6-1 or the following equation.

$CCS $/sq m [(1000 m) (3.7 m lane width)] = $CCS $/lane-km

STEP 4. Evaluate whether a more detailed analysis is justified.

A. If initial construction costs are lower with geosynthetic, use of a geosynthetic is justified. Perform a life-cycle cost analysis if cost savings over the life of the project must be quantified.

B. If initial construction costs are greater with the geosynthetic, cost benefits may be realized over the life of the project. Therefore, perform life-cycle cost analysis (see Section 6.4).

6.3 INITIAL CONSTRUCTION COST CASE HISTORY

Huntington and Ksaibati (1999) documented costs and performance of a Wyoming Department of Transportation experimental base reinforcement project. This project included construction of two pavement sections, one reinforced and the other unreinforced, designed to provide equivalent performance. The unreinforced pavement section consists of 20 mm open-graded friction course, 100 mm hot plant mix bituminous pavement, and 430 mm granular base. The reinforced section was designed on a base course reduction (BCR) percentage. It consists of 20 mm open-graded friction course, 100 mm hot plant mix bituminous pavement, 280 mm granular base, and geogrid reinforcement. In each section, the granular base is a 50/50 mixture of cold-milled reclaimed asphalt pavement and crushed virgin aggregate. The extruded geogrid was placed at the mid-depth of the granular base. The pavement sections were constructed in 1995. To date, the performance of the two sections has been equivalent based on: (i) pavement condition surveys; (ii) rut measurements; and by FWD measurements and analyses.

Initial construction cost economics from this project are presented in Table 6-1. Note that the base course reduction is significant (150 mm), but that the base course material cost was relatively low ($3.86/tonne, without haul costs). In-place granular base costs are inclusive of haul cost. While reducing initial construction cost was the objective of this application, analyses of measurements to date suggest a serviceability advantage over time with the geogrid section, thus leading to additional life-cycle cost value.

Table 6-1. Cost Comparison of Base Materials With and Without Geogrid Reinforcement (after Huntington and Ksaibati, 1999)

In-Place Granular Base Cost	Cost/km		
	No Geogrid	In-Place Geogrid Cost	
		$1.75/m^2	$2.50/m^2
$3.86/tonne	$55,407	$59,344	$70,594
$4.36/tonne	$62,539	$63,604	$74,854
$4.85/tonne	$69,671	$67,863	$79,113
$5.84/tonne	$83,934	$76,383	$87,633
$8.36/tonne	$120,369	$98,144	$109,394
$8.81/tonne	$126,724	$101,940	$113,190
$13.76/tonne	$198,040	$144,537	$155,787

6.4 LIFE-CYCLE COSTS

There are many costs and additional factors to be considered in a life-cycle cost analysis. The major initial and recurring costs that should be considered in the economic evaluation of alternative pavement strategies [e.g., whether to reinforce with a geosynthetic] include the following (AASHTO, 1993):

(1) Agency costs:
   a. Initial construction costs
   b. Future construction or rehabilitation costs (overlays, seal coats, reconstruction, etc.)
   c. Maintenance costs, recurring throughout the design period
   d. Salvage return or residual value at the end of the design period (may be a "negative cost")
   e. Engineering and administration costs
   f. Traffic control costs, if any are involved

(2) Use costs:
   a. Travel time
   b. Vehicle operation
   c. Accidents
   d. Discomfort
   e. Time delay and extra vehicle operating costs during resurfacing or major maintenance

Factors that must be defined for a life-cycle analysis include the following: analysis period; performance period; equivalent single axle loads (ESALs) over initial performance period; initial and terminal serviceability values; discount rate; pavement component thicknesses; pavement components structural coefficients; subgrade resilient modulus; annual maintenance costs; initial construction costs; and rehabilitation construction costs. Pavement management systems can greatly assist in evaluating the cost of alternatives and can be used to estimate the cost of extending service life through use of geosynthetic reinforcement. Such a large number of variables preclude development of general graphs for computing cost savings (see, Figure 6-1). Clearly, life-cycle cost analyses must be performed on an individual agency basis and/or project basis.

Several alternatives should be analyzed with life-cycle costs. Example options that may be evaluated are listed in Table 6-2. The thickness of the pavement materials may vary with the options. Other options may be developed by varying (i) the type or strength of reinforcement;

Table 6-2. Design Options to Compare with Life-Cycle Cost Analysis

Design Option	Unreinforced	Reduced Base Course Thickness	Performance Period Extension	Combination
Pavement Option				
ACC Surface	__ mm	__ mm	__ mm	__ mm
ACC Binder	__ mm	__ mm	__ mm	__ mm
Base Course	__ mm	__ mm	__ mm	__ mm
Subbase Course	__ mm	__ mm	__ mm	__ mm
Reduced Over-Excavation[a]	none	__ mm	__ mm	__ mm
Geosynthetic Reinforcement	none	YES	YES	YES
Analysis Period (yrs)				
Performance Period (yrs)				
Initial Construction Cost ($/lane-km)				
Total Life-Cycle[b] **Cost ($/lane-km)**				
Percent Savings from Unreinforced Design	N/A			

Note: a. Note any undercut reduction due to geosynthetic.
b. In today's dollars.

(ii) the reinforcement design procedure used; or (iii) the base course material (strength and drainage characteristics). The analysis period will likely be the same for all options, but the performance period may vary. Initial construction and life-cycle costs will vary for the options examined. Life-cycle cost savings, or additional cost, of the reinforcement design options to the unreinforced option can be compared.

6.5 EXAMPLE LIFE-CYCLE COST ANALYSES

Four example life-cycle cost calculations are presented in Appendix C. The calculations are based upon 5,000,000 equivalent single axle loads (ESALs) over the analysis period. The first computation is for an unreinforced pavement structure. The unreinforced example provides the basis for comparison of the geosynthetic reinforcement examples. Input parameters used in the example calculations are listed in Table 6-3.

Table 6-3. Parameters Used in Life-Cycle Cost Examples

Parameter	Value
Initial Serviceability	4.2
Terminal Serviceability	2
Reliability Level	85
Overall Standard Deviation	0.49
Subgrade Resilient Modulus	80 MPa
Structural Design Number	3.37
Initial Construction Costs Asphalt Aggregate Base Course	 $38.57/tonne $22.04/tonne[a]
Maintenance — initiates 5 yrs after construction or rehabilitation Annual cost	 $161/lane km
Discount Rate	3.50
Evaluation Method	NPV
Salvage Value	0
Note: a. From Means, 1990.	

The second computation is a reduced base course thickness. The geosynthetic reinforcement is used to decrease the required aggregate base course thickness. The performance period is extended in the third computation. The geosynthetic reinforcement is used to increase the performance period (i.e., time to rehabilitation), and uses the same base course thickness as the unreinforced example.

The fourth computation combines a base course reduction and extension of the performance periods. The geosynthetic reinforcement is used to increase the performance period (i.e., time to rehabilitation) and to reduce the base course thickness. A summary of the results of the analyses is presented in Table 6-4. The example life-cycle cost analyses were performed with the AASHTO DARWIN™ computer program.

Table 6-4. Summary of Example Life-Cycle Cost Analyses

ESAL/ Analysis Period	5,000,000			
Design Option	**Unreinforced**	**Reduced Base Course Thickness**	**Performance Period Extension**	**Combination**
Pavement Option				
ACC Surface	38 mm	38 mm	38 mm	38 mm
ACC Binder	64 mm	68 mm	68 mm	68 mm
Base Course	305 mm	254 mm	305 mm	305 mm
Reduced Over-Excav.	none	51 mm	0	51 mm
Geosyn. Reinforcement	none	YES	YES	YES
— In-Place Cost	n/a	$1.79/sq m	$1.79/sq m	$ 3.11 sq m
— TBR Value	n/a	n/a	2.0	2.6
— BCR Value	n/a	17%	n/a	n/a
— LCR Value	n/a	n/a	n/a	n/a
Analysis Period (yrs)	40			
Performance Period (yrs)	10	10	20	20
Initial Construction Cost ($/lane-km)	$90,402	$87,151	$98,638	$91,492
Total Life-cycle[a] Cost ($/lane-km)	$121,730	$117,228	$108,471	$100,977
Percent Savings Compared to Unreinforced Design	—	4%	11%	17%
Note: a. In today's dollars.				

6.6 ADDITIONAL BENEFITS OF GEOSYNTHETIC REINFORCEMENT

Geosynthetics are factory manufactured and have well-defined reliable material properties. Incorporation of geosynthetic reinforcement into a pavement adds a degree of redundancy in the structure. Thus, geosynthetic reinforcement of the base course of a flexible pavement, properly designed and installed, increases the reliability of a pavement and the likelihood of satisfactory performance of the pavement structure over the performance period.

Traffic volume (i.e., ESALs) is a significant input parameter for pavement designs, and can be difficult to accurately predict. Geosynthetic base course reinforcement, originally designed to extend the performance periods and decrease life-cycle costs, likely will ensure that at least the unreinforced pavement performance period is reached in roadways, with actual ESALs much greater than design ESALs. Geosynthetic reinforcement can provide similar performance on roadways, or sections of roadways, with subgrade strengths significantly lower than design subgrade strength.

[BLANK]

7.0 MATERIAL PROPERTIES

7.1 INTRODUCTION

Intuitively, the geosynthetic properties that should have the greatest impact on reinforcement performance are the geosynthetic modulus and the soil-geosynthetic interaction. Many studies on specific reinforcement product lines and types (e.g., extruded geogrids, knitted or woven geogrids, woven geotextiles, etc.) clearly show an improvement in performance with increased modulus. The range of modulus evaluated in these studies is shown in Table 2-4 for geotextiles and Table 2-5 for geogrids, based upon unconfined testing. The values based on 2% and 5% secant moduli determined by ASTM D 4595 (modified for geogrids), without offset, ranged from about 200 to 750 kN/m for woven geotextiles and about 160 to 400 kN/m for geogrids.

However, the relationship between geosynthetic modulus and performance was not clear from studies comparing the performance of different geosynthetics (see Tables 2-8 and 2-9). Some studies showed similar modulus geosynthetics performing with varying results; higher modulus geosynthetics performing with inferior results than lower modulus geosynthetics; and varying conditions sometimes reversing observed trends. Evaluating performance properties is difficult due to the large number of variables that exist in pavement design, as noted in Table 3-1. Another complicating feature is the positive influence of confinement (normal stresses) on the modulus value of many geosynthetics.

The interaction characteristics (frictional and interlock) also appear to play a key role. However, the influence of frictional characteristics for geotextiles has not been extensively evaluated. The measurement of interlock provided by geogrids has traditionally been through pullout resistance or direct shear. However, most of the studies reviewed did not evaluate pullout resistance or interface friction angle in relation to the soils in the test program. Aperture size of geogrids in relation to the adjacent base or subbase would appear to be an important factor, but this has not been extensively studied.

There is also some indication that aperture stiffness may have an influence on performance. Two studies found a correlation between the stiffness of geogrids and their performance (Webster, 1993; Kinney and Xiaolin, 1995). Stiffness of geogrids is often measured in terms of flexural rigidity (ASTM D 1388*) (Holtz, et al., 1998), junction strength (GRI:GG2), and most recently, aperture stability (or torsional stiffness) (Webster, 1993; Kinney and Xiaolin, 1995). However, current available information does not provide clear, quantifiable values for any of these properties specifically in relation to performance for highway conditions.

---

* ASTM D 1388 was discontinued 1995.

A definitive method of analysis relating specific geosynthetic properties to reinforced pavement performance has not been developed at this time. Although some relationships have been identified for some types of materials, until such relationships to performance are clearly identified for a majority of materials, reinforcement performance should be based on empirical evidence from both field and laboratory tests (i.e., as discussed in Section 5). Properties that mainly characterize the specific materials evaluated should be specified. In order to provide a future database reference, these properties should include the following: 1) (a) 2% and (b) 5% secant modulus based on wide width tests (ASTM D 4595 for geotextiles and ASTM D 4595 modified for geogrids); 2) coefficient of interaction based on pullout testing (GRI:GG5 for geogrids and GRI:GT6 for geotextiles); and 3) interface friction from direct shear (ASTM D 5321). Stiffness in terms of flexural rigidity, aperture stability and torsional stiffness are not included in the database list because test methods have not been standardized for geogrids and their relation to this application is currently being evaluated by the geosynthetics industry, as discussed in chapter 10.

Properties must also be considered in relation to construction survivability. The geosynthetic must survive the construction operations if it is to perform its intended function. AASHTO M288 (Appendix B) has established minimum geotextile properties to survive each level of construction, as listed in Appendix A. Minimum properties for geogrids have been established through an industry review (see GMA White Paper I). Survivability of geogrids and geotextiles for major projects should be verified by conducting field tests under site-specific conditions. Finally, where required for filtration, permeability and retention properties for geotextiles must be specified, and are addressed in AASHTO M288 and the FHWA manual (Holtz et al., 1998).

7.2 PAVED PERMANENT ROADS

7.2.1 Base/Subbase Reinforcement

Proprietary specifications for base (or subbase) reinforcement should be based upon laboratory TBR or BCR performance tests that have been correlated to field performance. All prospective manufacturers should be required to provide this data, or it should be developed by the agency. An approved products list could then be prepared based upon materials meeting the design requirements. The specifier should also require the manufacturer to submit characteristic properties for its materials, as outlined in Table 7-1, as part of the properties database for future evaluation. Properties required for constructability, installation survivability, and, if required, separation and filtration should also be included. Refer to GMA WP I for a discussion and listing of installation survivability properties.

Table 7-1. Characteristic Properties for Base and Subbase Reinforcement Applications, for Use in Development of a Database and Future Evaluation

Geosynthetic	Properties	Test Methods
Geotextiles	2% and 5% Secant Moduli[1] Coefficient of Pullout Interaction Coefficient of Direct Shear AOS Permittivity	ASTM D 4595 GRI GT6 ASTM D 5321 ASTM D 4751 ASTM D 4491
Geogrids[2]	2% and 5% Secant Moduli[1] Coefficient of Pullout Interaction Coefficient of Direct Shear Aperture Size Percent Open Area	ASTM D 4595 modified GRI GG5 ASTM D 5321 Direct Measure COE CW-02215
GG-GT Composites Bonded[2]	2% and 5% Secant Moduli[1] Coefficient of Pullout Interaction Coefficient of Direct Shear Aperture Size AOS Permittivity	ASTM D 4595 GRI GT6 ASTM D 5321 Direct Measure ASTM D 4751 ASTM D 4491
GG-GT Composites Unbonded	— Use Geotextile and Geogrid recommendations	

Note: 1. Measured without offset.
2. Stiffness properties including flexural rigidity and aperture stability are currently being evaluated by the geosynthetic industry, in regards to this application; see Chapter 10 for additional discussion.

7.2.2 Subgrade Restraint/Stabilization

Subgrade restraint is the reinforcing component within stabilization applications. Generic property values can be specified for subgrade restraint and stabilization applications with several design procedures (e.g., Holtz et al., 1998). Subgrade restraint design is essentially the same as stabilization design, except that a reinforcement modulus value may be required in addition to the properties of interest in stabilization, which are related to filtration requirements and survivability. For subgrade restraint, a minimum modulus value may be determined from the Giroud and Noiray (1981) design procedure or the Bender and Barenburg procedure (1980). It should be noted that these design procedures require some rutting of the initial construction lift to develop modulus requirements. Other subgrade restraint design procedures are based upon empirical performance with specific materials, and an approved products specification — in lieu of generic properties — is appropriate. Table 7-2 provides a listing of the property requirements for subgrade restraint applications. Refer to GMA WP I for a discussion and listing of installation survivability properties.

Table 7-2. Characteristic Property Requirements for Subgrade Restraint Applications

Geosynthetic	Properties	Test Methods
Geotextiles — Characteristic Performance — Installation Survivability	2% and 5% Secant Moduli[1] AOS Permittivity — see GMA WP I	ASTM D 4595 ASTM D 4751 ASTM D 4491 —
Geogrids — Characteristic Performance — Installation Survivability	2% and 5% Secant Moduli[1] Aperture Size Percent Open Area — see GMA WP I	ASTM D 4595 modified Direct Measure COE CW-02215 —
GG-GT Composites - Bonded — Characteristic Performance — Installation Survivability	2% and 5% Secant Moduli[1] AOS Permittivity — see GMA WP I	ASTM D 4595 ASTM D 4751 ASTM D 4491 —
GG-GT Composites - Unbonded	— Use Geotextile and Geogrid recommendations	—
Note: 1. Measured without offset — optional requirement depending on design procedure and the tolerable rutting of the initial construction lift. 2. This table supercedes specification properties listed in GMA White Paper I, except the installation survivability properties.		

7.3 OTHER APPLICATIONS

The subgrade restraint property requirements for paved, permanent roads in Table 7-2 are also applicable for temporary unpaved and paved, and permanent unpaved road applications.

8.0 RECOMMENDED PRACTICE

8.1 INTRODUCTION

The use of geosynthetics in roadway pavements has evolved from the 1960s and 1970s, when the materials were used to solve problems, to today when geosynthetics are designed into the pavement structure to enhance performance and economics. The design practices presented within this section pertain to geosynthetics designed into a pavement structure.

General steps for incorporating a geosynthetic reinforcement element into a pavement structure are outlined in Section 8.2. Specific steps for base, or subbase, paved permanent roads are presented in Section 8.3. Design for support of equipment during construction is summarized in Section 8.4.

The specific steps presented and discussed in Section 8.3 provide a logical approach for engineering geosynthetic reinforcement in paved permanent roads. The logic is based upon current knowledge. It is anticipated that a broader applicability of geosynthetic reinforcement will be defined as additional experience is gained.

8.2 DESIGNING WITH GEOSYNTHETIC REINFORCEMENT

Geosynthetic reinforcement is used in roadways to aid in support of traffic loads, where loads may be vehicular loads over the life of the pavement or equipment loads on the unpaved base, or subbase, course during construction. The type of load to be supported dictates the approach to design, and the resulting material specification. Function, and design, can be categorized as either *base reinforcement* or as *subgrade restraint*.

Base reinforcement design is the use of a geosynthetic as a tensile element placed at the bottom or within a base course (or beneath a subbase) to (1) improve the service life, and/or (2) obtain equivalent performance with a reduced structural section. Service life improvement may result in greater performance periods or increased safety factors on the predicted/design ESALs or the design subgrade strength. The primary mechanism associated with this application is lateral restraint or confinement. Base reinforcement is typically applied to support vehicular traffic over the life of the pavement structure. Base reinforcement design is addressed in Section 8.3.

Subgrade restraint design is the placement of a geosynthetic at the subgrade/subbase or subgrade/base interface to increase support of construction equipment over a weak subgrade. The primary mechanism with this application is increased bearing capacity, although lateral restraint and/or tension membrane effects may also contribute to load-carrying. Often accompanying the reinforcing function for this application is a need for separation and filtration. Subgrade restraint reinforcement design is addressed in Section 8.4.

For some projects, particularly those with a base and subbase, two layers of geosynthetic reinforcement may be used to provide both subgrade restraint and base reinforcement. Each layer of reinforcement may be independently designed for such applications.

8.3 BASE REINFORCEMENT DESIGN FOR PAVED PERMANENT ROADS

A general flow chart for designing geosynthetic pavement reinforcement, including assessment of reinforcement applicability for a particular project, is presented in Figure 8-1. Nine general design steps are identified in the flow chart. The applicability of geosynthetic reinforcement should initially be assessed by examining project conditions and comparing them to conditions favorable or unfavorable to the use of geosynthetic reinforcement. Table 4-1 should be used for this initial assessment, for asphalt paved permanent roads. Typical subgrade strength, base course thickness (with reinforcement), and geosynthetic type are variables noted in Table 4-1.

Steps for designing geosynthetic base reinforcement are presented in Section 8.3.1. These steps follow the general flow chart for design presented in Figure 8-1. These design steps are for use on a project-specific basis, for flexible pavement structures. Comments on the design steps are presented in Section 8.3.2.

8.3.1 Design Steps

STEP 1. Initial assessment of geosynthetic reinforcement applicability.

A. Bracket in situ subgrade strength, in terms of CBR, resilient modulus (M_R), or undrained shear strength (c_u). Define design subgrade strength as either (i) low; (ii) moderate; or (iii) firmer.

B. Bracket base and subbase thickness, for unreinforced pavement structure.

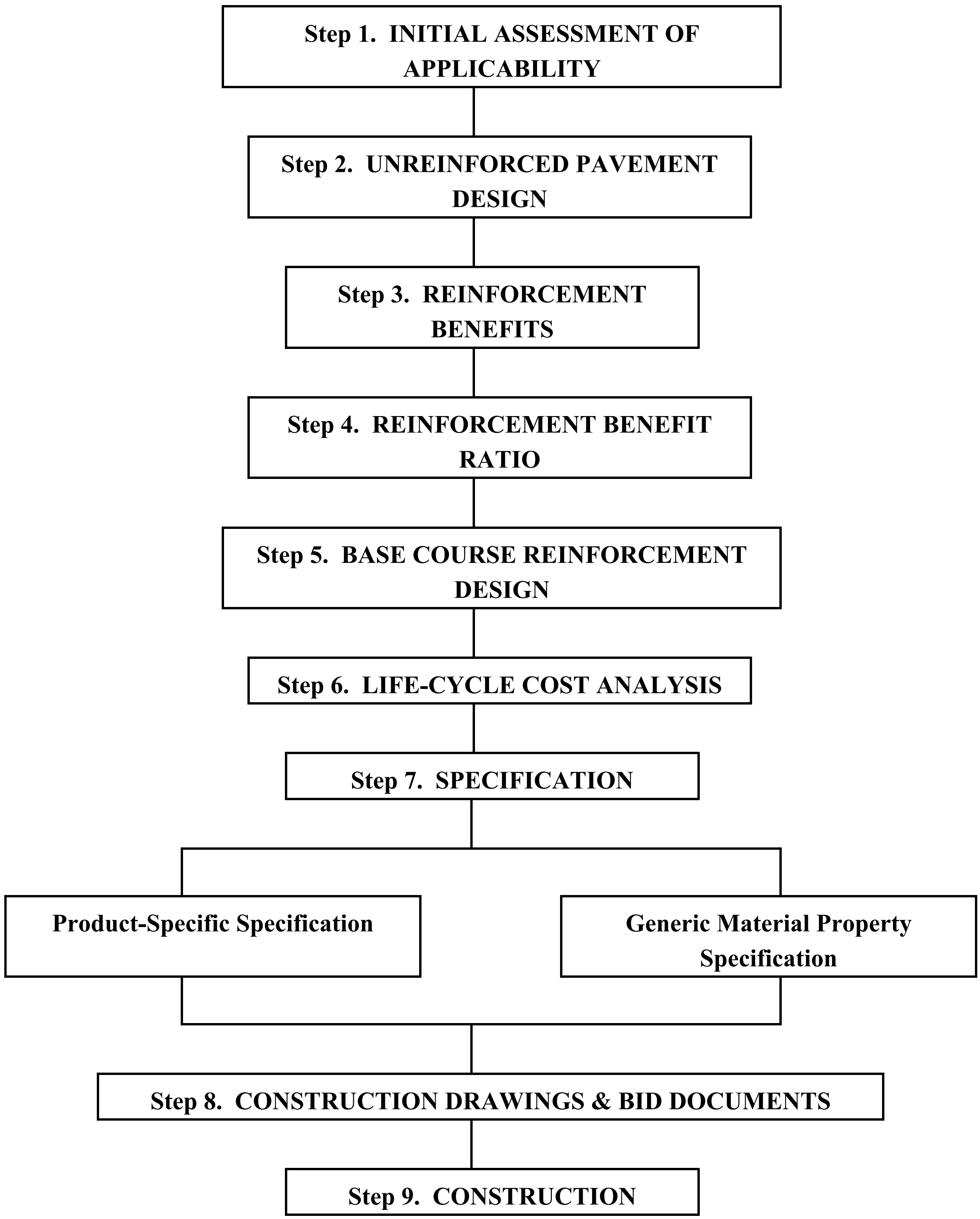


Figure 8-1. Design of geosynthetic reinforced pavements.

C. Estimate reinforced base and subbase thickness, assuming (i) same thicknesses as unreinforced case (i.e., reinforcement will be used to extend performance period); or (ii) a potential of 20-50% subbase or base course thickness reduction (usually a maximum of 75-125 mm is used, as this usually provides a sufficient level of initial cost savings), with geosynthetic reinforcement.

D. Define subbase and base course gradation, as open-graded or well-graded. Define the drainage coefficient modifier, m, for the base and subbase.

E. Classify project conditions by subgrade strength, reinforced base or subbase thickness, and subbase and/or base gradation.
   i. Subgrade strength —
      a. Low ($CBR < 3$),
      b. Moderate ($3 \leq CBR \leq 8$), or
      c. Firmer ($CBR > 8$)
   ii. Reinforced base or subbase thickness —
      a. 150 mm - 300 mm
      b. $\geq$ 300 mm
   iii. Subbase and/or base gradation —
      a. Open-graded (check if geotextile filter is required)
      b. Well-graded (check conformance with drainage and filtration requirement)

F. Determine applicability of geosynthetic types (geotextile, geogrid, and geogrid-geotextile composite) using Table 4-1 — Qualitative review of reinforcement application potential for paved permanent roads. Geosynthetic types are classified as either usually applicable; applicable for some cases; usually not applicable; or insufficient information at this time. List applicable geosynthetic types.

STEP 2. Unreinforced pavement thickness design.

A. List unreinforced design procedure.

B. Select representative material parameters for unreinforced pavement design, from bracketed values (Step 1).

C. Size subbase course, base course, and excavation thicknesses without geosynthetic
.

STEP 3. List benefits of using geosynthetic reinforcement.

A. Review benefits for which cost savings are quantifiable using Table 3-3 — Reinforcement benefits for paved permanent roads, and for the project subgrade strength classification.

B. List target benefit for this design. Will reinforcement be used to (i) extend performance period; (ii) decrease base or subbase thickness; or (iii) a combination of performance period extension and thickness reduction? Will design decrease the amount of over-excavation?

STEP 4. Definition of reinforcement benefit ratio.

A. Target benefit, from Step 3.B, identifies whether a TBR or a BCR ratio must be defined. A TBR can be used for all three of the possible target benefits. A BCR can be used with the decreased base, or subbase, thickness option. Note that some procedures are based upon an LCR, which can be used with all three possible target benefits.

B. List project conditions for comparison to research conditions used to define TBR, BCR, or LCR.

C. Obtain TBR, BCR, or LCR from lab test results that have been correlated to field tests conducted using the same geosynthetic reinforcement. Compare research and experience conditions to project conditions, for each possible reinforcement material. An example comparison is presented in Table 8-1.

D. Select an appropriate, empirical TBR, BCR, or LCR value, based upon the comparison table, or conduct tests to define value — see Appendix E.

E. Reasonableness of selected TBR, BCR, or LCR value and reliability of the reinforced pavement should be qualitatively evaluated. An impractical performance period, i.e., greater than historical rehabilitation periods based upon environmental factors, should not be used with a TBR-based design. (TBR defined by rut depth over time, without consideration of environmental factors.) The reliability of a reinforced pavement structure designed on a basis of TBR is likely

Table 8-1. Example for Comparison of Product-specific Values to Project-specific Conditions

Variable	Project Conditions[1]	Research Studies[2]						Similar Projects[2]			
		Full-Scale Field			Laboratory						
		A	B	C	A	B	C	A	B	C	D
Reinforcement — Type — Location											
Failure Criteria (e.g., __ mm rut depth)											
Loading Type Cyclic Load Cyclic Pressure Load Frequency											
Asphalt — material — thickness											
Base Course — material — thickness — angularity — gradation — CBR											
Subbase — material — thickness — CBR											
Subgrade — material — strength											
Filter — need for — soil or geosynthetic											
Years Installed											
TBR Value											
BCR Value											

Notes: 1. Project or agency conditions. Insert values or range of values.
2. Insert columns as needed to list all relevant full-scale field and laboratory studies, and similar projects.

higher than an unreinforced pavement, due to the redundancy added by the reinforcement. Reliability of a reinforced pavement designed on a basis of BCR might be, depending on how the designer defined the BCR value, assumed to be lower than the reliability of an unreinforced pavement structure.

STEP 5. Reinforced pavement design.

A. Design for extension of performance periods.

i. Design with a TBR

The design TBR may be used to compute an extended performance period. The pavement geometry does not differ from the unreinforced construction option. The design TBR is used to compute years before rehabilitation. For the unreinforced case:

$$Years\ \ before\ \ Rehab \;=\; \frac{W_{18}}{ESALs/year}$$

where:

W_{18} = predicted number of 18-kip equivalent single axle load applications, and

ESAL = equivalent single axle loads

For the reinforced case, the TBR is applied to compute an adjusted, or equivalent reinforced, number of 18-kip equivalent single-axle load applications. The equivalent reinforced value is:

$$(W_{18})_R \;=\; W_{18}\ x\ TBR$$

With this equivalent value, the years before rehabilitation is computed as:

$$Years\ \ before\ \ Rehab \;=\; \frac{(\ W_{18}\ )_R}{ESALs/year}$$

ii. Design with an LCR

An indirect computation method (and not the recommended practice), the design LCR may be used to compute an extended performance period. The base course layer coefficient ratio (LCR) is applied to the structural number equation as:

$$SN = a_1 D_1 + LCR\ a_2 D_2 m_2 + a_3 D_3 m_3$$

With the base course thickness held constant, the structural number of the reinforced section increases. This increased structural number leads to an extended service life of the pavement. Alternatively, a design LCR may be applied to the subbase.

B. Design for reduction of aggregate base thickness.

i. Design with a BCR ratio

The design BCR may be used to compute a reduced base, or subbase, thickness to provide the same performance as the unreinforced pavement structure. The reinforced base course thickness, $D_{2(R)}$, is computed (without a subbase) as:

$$D_{2\,(R)} = D_{2\,(UNREINF)}\ x\ (1 - BCR)$$

ii. Design with a TBR

An indirect computation method, the TBR may be used to compute an adjusted structural number, SN_R. The reinforced structural number is computed with the $(W_{18})_R$ (Step 5.A) in the pavement design equation. The reduced depth of aggregate, with the reinforcement, is then computed as:

$$D_{2(R)} = \frac{SN_R - a_1 D_1}{a_2 m_2}$$

Check that the design TBR values is applicable for the computed (reduced) base course thickness.

iii. Design with an LCR

An indirect computation method, the design LCR may be used to compute a reduced thickness of aggregate. The layer coefficient ratio (LCR) is applied to the structural number equation as:

$$SN = a_1 D_1 + LCR\ a_2 D_2 m_2$$

The reduced, reinforced aggregate thickness is equal to:

$$D_{2(R)} = \frac{SN - a_1 D_1}{LCR\ a_2\ m_2}$$

Check that the design TBR values is applicable for the computed (reduced) base course thickness.

C. Design for combination of some extension of performance period and some reduction of aggregate base thickness. A combination of benefits can be achieved by selecting a base course thickness greater than $D_{2\,(R)}$ and less than D_2 (Step 5.B), resulting in a performance period sometime between the unreinforced and reinforced case (Step 5.A). Check that the design TBR values is applicable for the partially reduced base course thickness. Similarly, the subbase could be reinforced and reduced partially in thickness.

D. Separation and filtration.
A properly designed geosynthetic placed at the interface between the aggregate base, or subbase, course and the subgrade functions as a separator to prevent two dissimilar materials (subgrade soils and aggregates) from intermixing. Geogrids, geotextiles, and GG-GT composites perform this function by preventing penetration of the aggregate into the subgrade. In addition, geotextiles and GG-GT composites prevent intrusion of subgrade soils up into the base course aggregate.

A filter above the subgrade is required with a geogrid reinforcement if the subgrade is wet and fines can *pump* or migrate up into the base, or subbase, course. The filter may be a soil (e.g., well graded base or subbase, sand subbase, etc.) or a geotextile. The compatibility of either filter material (soil or geotextile) must be checked with respect to the subgrade based on the following criteria:

i. Soil filter requirements: Cedergren, 1989

ii. Geotextile filter requirements: AASHTO M288 and Holtz et al., 1998

STEP 6. Life-cycle cost assessment.

A. Compute initial construction costs for pavement:
   i. Unreinforced

ii. Reinforced per design option
iii. Other options

B. Compute life-cycle costs for pavement:
i. Unreinforced
ii. Reinforced per design option
iii. Other options

C. List benefits of reinforcement that are not quantifiable in a dollar amount.

D. Compare financial, and other benefits, and select option(s) to use in final design and specification. A few options may be carried forward because relative estimated costs — and other benefits — are similar and/or because one (or more) option(s) use a proprietary product (i.e., design is based upon proprietary parameter(s)).

STEP 7. Specification.

A. Prepare specification(s) for design option(s).

STEP 8. Incorporate design features into construction drawings and bid documents.

STEP 9. Observe construction.

8.3.2 Comments on Design Steps

STEP 1. Initial assessment of applicability.

Follow traditional geotechnical practice to define in situ subgrade strength. A range of strength may be appropriate for projects with varying conditions along the roadway alignment and over seasonal variations (e.g., AASHTO method (1993)). A design strength may be at the lower end of the range, and this value would be used to assess applicability of geosynthetic reinforcement. If the selected design strength is between the upper and lower bound strengths, geosynthetic applicability should be assessed at the design strength and at the lower bound strength value. In some cases, geosynthetics may be used to reinforce only the sections of the project that have the subgrade strength lower than the design strength value. This may allow constant thicknesses of asphalt and aggregate along the project length.

Bracket base and subbase thicknesses for the unreinforced pavement. Aggregate thickness may range from calculated thickness to rounded-up, constructable thickness, or may reflect the difference between the lower bound and design subgrade strengths.

Definitions of subbase or base course gradation and subgrade moisture conditions are needed to assess whether a filter is required between the subgrade and aggregate (subbase or base). Traditional soil filtration criteria have been used to assess whether the subbase, or base, will serve as a filter. If not, a geotextile filter is required. Procedures for geotextile filtration design are contained within FHWA Geosynthetic Design and Construction Guidelines manual (Holtz, et al., 1998). When in doubt, use of a filtration geotextile is advisable.

Classification of project by subgrade strength and base/subbase thickness is needed to use applicability and design procedure tables. Gradation of base and subbase are required to assess their quality of drainage. Design options that use different base, or subbase, materials should include the effect of drainage on the designs. The effect of drainage is incorporated into the AASHTO (1993) design method through use of a modifier applied to the base and subbase components in the structural number equation. The values used in the AASHTO method are listed in Table 8-2.

STEP 2. Unreinforced pavement design.

Thicknesses for pavement components, without geosynthetic reinforcement, should be calculated with normal procedures. An average over-excavation depth (i.e., required excavation depth beyond stripping limits) should be calculated.

Table 8-2. Recommended m_i Values for Modifying Structural Layer Coefficients of Untreated Base and Subbase Materials in Flexible Pavements (from AASHTO, 1993)

	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
Quality of Drainage	**Less Than 1%**	**1 - 5%**	**5 - 25%**	**Greater Than 25%**
Excellent	1.40 - 1.35	1.35 - 1.30	1.30 - 1.20	1.20
Good	1.35 - 1.25	1.25 - 1.15	1.15 - 1.00	1.00
Fair	1.25 - 1.15	1.15 - 1.05	1.00 - 0.80	0.80
Poor	1.15 - 1.05	1.05 - 0.80	0.80 - 0.60	0.60
Very Poor	1.05 - 0.95	0.95 - 0.75	0.75 - 0.40	0.40

STEP 3. Reinforcement benefits.

Some benefits can be quantified in terms of initial construction cost savings or life-cycle cost savings. Cost savings are not readily quantifiable for other benefits, such as increased reliability, redundancy, etc. Both types of benefits should be considered in the applicability assessment.

Selection of the target benefit should consider the current degree of experience with geosynthetic reinforcement of flexible pavements. Although current research strongly supports the design procedure contained herein, reliable long-term project performance information based on these procedures is not available at this time. It is recommended that agencies with limited experience with geosynthetic reinforcement primarily use the reinforcement to improve the service life of pavement structures, and limit reduction of the structural section until more experience is gained.

STEP 4. Reinforcement benefit ratio.

Agency-specific evaluation of research to select appropriate empirical TBR or BCR (or LCR) ratio is recommended. Such evaluation should be tailored to local materials, practice, and costs. Furthermore, agency-specific evaluation of research should provide designers with guidance on the value of reliability for the reinforced pavement.

STEP 5. Base course reinforcement design.

One or more procedures may be available for design of the geosynthetic reinforced pavement structure, depending on project classification (i.e., subgrade strength and base/subbase thickness). Designers may use more than one procedure and compare computed results and benefits.

Size subbase course, base course, and over-excavation thicknesses with geosynthetic reinforcement for the various design options.

Economics should be examined for the unreinforced pavement and reinforced options (i.e., thickness decrease, increase design life, or combination). Economics should be examined for both initial construction costs and for life-cycle costs. Some design procedures can be used to optimize either the initial or the life-cycle cost savings, and the designer should optimize the design to meet the agency's needs. For some projects and design procedures, initial construction costs with geosynthetic reinforcement may be set approximately equal to the construction cost of an unreinforced pavement and will provide significant life-cycle cost savings.

Examine initial results and perform calculations for additional options. The additional options may focus on the agency-desired type of cost savings for a particular design procedure.

STEP 6. Life-cycle cost analysis.

List costs, both initial and life-cycle, and the benefits that cannot be quantified in dollar amount for the various design options. Compare costs and benefits of any options, and select option(s) to carry forward into the final design and specification. The designer may select to carry forward (i) one option for a reinforced pavement; (ii) two options — one for a reinforced pavement and another for an unreinforced pavement; (iii) multiple pavement reinforcement options; or (iv) multiple pavement reinforcement options and an unreinforced option.

Benefits of reinforcement that are not quantifiable in a dollar amount should be factored into the design decision process. These benefits may include: reduced disturbance of the subgrade during construction; improved reliability of pavement structure (for TBR-based design); and redundancy in structural support.

STEP 7. Specification preparation.

Prepare specification(s) for design option(s). Editable material specifications are discussed in Section 8.5 for geogrid, geotextile, and geogrid-geotextile composite materials. Proposed editable material specifications are presented in Appendix D. These are material specifications for purchasing and do not address installation.

STEP 8. Incorporate design features into construction drawings and bid documents.

Provide consistency between documents.

STEP 9. Observe construction.

Inspection should be performed by a trained and knowledgeable inspector, and good documentation of construction should be maintained.

8.4 SUBGRADE RESTRAINT DESIGN FOR PAVED PERMANENT ROADS

8.4.1 Background

Subgrade restraint may occur when a geosynthetic is placed at the subgrade/subbase or subgrade/base interface to increase the support of construction equipment over a weak subgrade. Subgrade restraint may be used for construction of flexible or rigid pavements. The primary mechanism associated with this application is increased bearing capacity, although lateral restraint and/or tension membrane effects may also contribute to load-carrying. Accompanying the reinforcing function for this application is a need for filtration, either provided by the subbase (or base) or a geotextile.

A method for designing a pavement with geosynthetic subgrade restraint is presented below. This design method is for use on a project-specific basis. The various design procedures for computing the load-carrying capacity of the geosynthetic subgrade restraint, listed in Table 5-2, can be used in Step 5 of this method. The various design procedures for subgrade restraint, unlike base reinforcement, are well documented in technical journals. Designers are referred to the literature listed in Table 5-2 for details on design for subgrade restraint. Many of these procedures are modifications of Barenburg (1980); Stewart et al. (1977); Giroud and Noiray (1982); or FHWA (Christopher and Holtz, 1985; Holtz, et al., 1998).

8.4.2 Design Steps

STEP 1. Initial assessment of geosynthetic applicability.

A. Estimate the need for a geotextile, based on subgrade strength and past performance in similar soil types.

B. Determine applicability of geosynthetic types (geotextile, geogrid, and geogrid-geotextile composite) using Table 4-1 — Qualitative review of reinforcement application potential for paved permanent roads. Geosynthetic types are classified as either usually applicable; applicable for some cases; usually not applicable; or insufficient information at this time. List applicable geosynthetic types.

STEP 2. Unreinforced pavement thickness design.

A. List unreinforced design procedure.

B. Select representative material parameters for unreinforced pavement design.

C. Size subbase course, base course, and excavation thicknesses without geosynthetic reinforcement.

STEP 3. Determine aggregate depth required to support construction equipment.

A. List allowable rutting depth. Consider whether or not traffic will be channelized and tension membrane support can occur; or if substantial wander may occur and tension membrane will not develop.

B. Determine the additional aggregate (to the base and subbase design thicknesses) required for stabilization of the subgrade during construction activities. A procedure listed in Table 5-2 may be used for this determination. These procedures vary on the basis of rut depth and geosynthetic functions. Design procedures may be based upon the geosynthetic functioning as a

i. Separator and filter;
ii. Separator (in which case, the base or subbase must perform as a filter);
iii. Separator, filter, and reinforcement; or
iv. Separator and reinforcement (in which case, the base or subbase must perform as a filter).

STEP 4. Check filtration.

A. If a geotextile or GG-GT composite is used, check the geotextile filtration criteria (e.g., AASHTO M288; Holtz et al., 1998) using the gradation and permeability of the subgrade, the water table conditions, and the geotextile retention and permeability criteria.

B. If a geogrid is used alone, check soil filtration criteria (e.g., Cedergren, 1989) between the subgrade and subbase or subgrade and base.

STEP 5. Determine geosynthetic survivability requirements.

Check the geosynthetic strength requirements for survivability from construction installation (addressed in GMA White paper I).

STEP 6. Specification.

Prepare specification(s) for design option(s) and for geosynthetics that meet or exceed survivability criteria.

STEP 7. Incorporate design features into construction drawings and bid documents.

STEP 8. Observe construction.

8.5 GEOSYNTHETIC REINFORCEMENT MATERIAL SPECIFICATION FOR PAVED PERMANENT ROADS

8.5.1 Specification Options

There are two primary options for specification of geosynthetics used to reinforce base, or subbase, course of pavement structures. The options are to:

(i) specify specific products via an approved products list, with equivalency defined by performance requirements; or

(ii) specify by generic material properties.

Only option (i) is appropriate for base reinforcement applications (see Section 9.1 discussion). Both options are appropriate for subgrade restraint applications.

The generic specification option is typically preferred by agencies, but it only may be used if the design procedure lends itself to generic specification of the geosynthetic reinforcement. If a product-specific design is used, a specific product or sole-source specification (e.g., typically acceptable with government agencies for experimental or demonstration projects) is required.

With a specific product design and specification, competitive bidding may be achieved by providing a design and bid option for both the reinforced and unreinforced option (thicker section to achieve same performance). Competitive bidding can also be achieved through multiple reinforcement design procedures and approved products.

8.5.2 Geogrid Reinforcement

A recommended material specification for geogrid reinforcement is attached in Appendix D. This material specification is for purchasing and does not address installation. Edit notes are presented in the right-hand column and should be used to modify the specification to match selected design option(s). Three principle specification options are presented: approved products list, performance properties, and generic material properties. This specification may be used with base reinforcement or subgrade restraint designs.

The specification is a modification of the geogrid specification presented in the Geosynthetic Materials Association's White Paper I (1999), prepared for the AASHTO 4E Task Group on geosynthetic reinforcement of pavements.

8.5.3 Geotextile Reinforcement

A recommended material specification for geotextile reinforcement is attached in Appendix D. This material specification is for purchasing and does not address installation. The specification is in a format similar to the AASHTO M288 specification. However, edit notes are presented in the right-hand column, and should be used to modify the specification to match selected design option(s). This specification may be used with base reinforcement or subgrade restraint designs.

The specification is a modification of the geotextile specification presented in the Geosynthetic Materials Association's White Paper I (1999), prepared for the AASHTO 4E Task Group on geosynthetic reinforcement of pavements.

8.5.4 Geogrid-Geotextile Composite Reinforcement

A recommended material specification for geogrid-geotextile composite reinforcement is attached in Appendix D. This material specification is for purchasing and does not address installation. Edit notes are presented in the right-hand column, and should be used to modify the specification to match selected design option(s). Two principle specification options are presented: approved products list, and generic properties. This specification may be used with base reinforcement or subgrade restraint designs. Geogrid-geotextile composites were not addressed in the Geosynthetic Materials Association's White Paper I (1999) which was prepared for the AASHTO 4E Task Group on geosynthetic reinforcement of pavements.

[BLANK]

9.0 DISCUSSION

The goal of this report is to document the conditions under which geosynthetic reinforcements provide value-added benefits to pavement structures when the geosynthetic is contained at the bottom of, or within, the aggregate base (or below the subbase). This report specifically strives to meet the following objectives: (i) document (recommended) design criteria/protocol(s); (ii) document value added to pavements in reinforcement of the pavement structure; and (iii) develop/document recommended practices for design and material specification. The attainment of these objectives is discussed below.

9.1 DESIGN CRITERIA

A distinction between two types of pavement reinforcement has been presented in this document. Geosynthetic reinforcements are incorporated into permanent, paved road either as

- **base** (or subbase) **reinforcement** — in flexible pavements to aid in the support of vehicular loads over the life of the pavement; or
- **subgrade restraint/stabilization** for construction of flexible or rigid roadways over weak subgrade conditions to aid in support of equipment loads on the unpaved base, or subbase, course during construction.

Design procedures and specifications vary between a *base reinforcement* and a *subgrade restraint* application. Furthermore, procedures and specifications vary from the geotextile applications of separation and stabilization addressed in the AASHTO M288 specification.

Base reinforcement is used to either (i) extend the performance period of a pavement; (ii) reduce the base (or subbase) thickness; or (iii) create a combination of the two. The mechanisms of geosynthetic base reinforcement are not fully understood. Therefore, performance of geosynthetics in base reinforcement are product-specific. Laboratory and/or field tests with specific products, similar pavement materials and cross sections, and similar subgrade conditions are required to quantify the contribution of the geosynthetic reinforcement to the pavement performance.

Subgrade restraint/stabilization is used to reduce the subbase, or base, thickness and depth of over-excavation for pavement construction over weak subgrades. Generic material property, such as tensile modulus, is used in some design procedures. Other design procedures are based upon product-specific performance.

9.2 VALUE-ADDED BENEFITS

Geosynthetic reinforcements provide cost savings in construction and/or maintenance of pavements. Additional benefits of geosynthetic reinforcement, though not readily quantified in terms of cost savings, are discussed within and should be factored into the design and material selection process. Cost savings for subgrade restraint are usually demonstrated with initial construction cost savings. Cost effectiveness of base (or subbase) reinforcement should be assessed with a life-cycle cost analysis. Although, for some projects where base reinforcement is used to reduce thickness, an initial construction cost analysis may demonstrate a cost savings. Examples of value-added benefits with base reinforcement are presented within this report. However, life-cycle cost analyses and pavement designs are agency and/or project specific, as there are many variables incorporated in a life-cycle cost analysis. Therefore, the value-added benefit(s) with base reinforcement must be assessed on an individual agency basis. Guidelines for agency-specific assessment of cost savings are presented. Base (or subbase) reinforcement of flexible pavements will add value to some agencies, but not to others.

9.3 RECOMMENDED PRACTICES

Recommended practices address design procedures and specifications. The general applicability of geosynthetic reinforcement is summarized in Table 4-1. This table can be used to perform an initial applicability assessment of geosynthetic reinforcement types for various project conditions. Design procedures vary depending upon whether the reinforcement is being used to provide base (or subbase) reinforcement or subgrade restraint.

Design procedures for base reinforcement are not well documented in technical journals. Therefore, a step-by-step design procedure and commentary for base reinforcement are presented in this report. Design procedures use a traffic benefit ratio (TBR), base course reduction (BCR) percentage, or layer coefficient ratio (LCR) value. The manner in which geosynthetic material properties affect reinforcement benefit, defined by TBR, BCR, or LCR, are not fully understood at this time, and, therefore, such ratios are product-specific. This leads to product-specific design and specification with an approved products list. Specification equivalency can be stated on a performance basis (i.e., TBR, BCR, or LCR value for specific pavement geometry and material properties and failure criteria). This is unlike the AASHTO M288 specification where generically-defined index properties can be used to define equivalency between geotextiles.

Design procedures for subgrade restraint/stabilization are well documented in technical literature. A step-by-step procedure is presented in this report, with specific literature referenced for evaluation of geosynthetic and corresponding stabilization aggregate requirements. Several subgrade design procedures are based upon a specific geosynthetic material property, such as tensile modulus. Specifying by generic index material properties is appropriate when such design procedures are used. Other design procedures are predicated upon empirical, product-specific performance, similar to base reinforcement design procedures. With this design basis, an approved products specification approach is appropriate.

The designer should consider the reliability of empirical extrapolation of the product-specific reinforcement ratios used in base (or subbase) reinforcement and subgrade restraint designs. A designer may consider subgrade restraint reinforcement for construction equipment support a less critical application than base reinforcement for load-carrying over the analysis period of the pavement. Similarly, base reinforcement for extending the performance period may be considered less critical than reinforcement for decreasing the base course thickness.

[BLANK]

10.0 RESEARCH NEEDS

Material presented in this document has shown that knowledge pertaining to the application of geosynthetic reinforcement in flexible pavements has progressed considerably since work began in the early 1980s. From the current body of literature, a reasonable understanding exists, in an empirical sense, of how geosynthetics should be used in pavement reinforcement. Empirical understanding means that current pavement reinforcement design is unable to explicitly account for the many variables believed to influence geosynthetic benefit. These variables were described in Table 3-1 of this report. Current design procedures using reinforcement input parameters, such as TBR and BCR, are both product-specific and conditions-specific to the demonstration test sections. Of utmost need is a generic design procedure expressed in terms of material properties, for the pavement layer materials (asphalt concrete, base, subbase), subgrade materials, and geosynthetic materials composing the pavement system. In developing this generic design procedure more information is needed in the following areas:

1. The importance and relationship of geosynthetic material properties, including tensile modulus, permanent strain accumulation under cyclic loading, in-plane shear modulus characteristics (being reflective of the material's torsional rigidity), stiffness including tensile, flexural and torsional, and creep and stress relaxation properties, on reinforced pavement performance, and whether this set of performance properties is the same for geotextiles and geogrids.
2. The importance and relevant relationship of flexural rigidity of geogrids and GG-GT composites for base reinforcement and/or subgrade restraint applications. Standardized test method should be developed. (The geosynthetic industry is currently working to develop a test standard and advance research to evaluate these potential relationships.)
3. The importance and relevant relationship of aperture secant modulus value of geogrids and GG-GT composites for lateral restraint mechanism of base reinforcement. Standardization of an applicable test method is required.
4. The importance and relationship of geosynthetic-base aggregate interaction properties on reinforced pavement performance and how these properties should be defined.
5. Whether interaction properties should be defined in terms of friction coefficients and/or stiffness parameters (i.e., gross slip or small displacement characteristics).
6. The importance of aggregate gradation and particle size on reinforcement benefit, as evidenced by geosynthetic-base aggregate interaction properties.
7. How optimal placement position of the geosynthetic within the base course layer is influenced by section layer thickness and the magnitude and dimensions of the anticipated traffic load.
8. The relationship of subgrade strength and stiffness properties on reinforced pavement

performance, as compared to an equivalent unreinforced section, and how reinforcement benefit is influenced by magnitude, geometry and wander of traffic load.

9. When and by how much the introduction of reinforcement can reduce base course thickness.
10. The validity of using TBR to work backwards to a reduction in base course thickness ratio (BCR).
11. The validity of combining benefits of an extension of life, as defined by TBR, and base course thickness reduction, defined by BCR, in a design solution.
12. The potential utility of nonwoven geotextiles, with high interaction coefficients, for paved roadway applications.
13. Whether plate load tests give higher TBR and/or BCR values than moving wheel load tests; if so, why; and if so, how results from plate load tests should be corrected for field conditions.
14. Application of geosynthetics for reinforcing poor quality base course material over low, moderate, and firmer subgrades.
15. The importance and relationship of geosynthetic modulus in subgrade restraint/stabilization applications.
16. Reliability of design methods.
17. Reproducibility of research results.

The approach used for examination of these issues should involve a combination of experimental test section work and numerical modeling work. The test section work is needed to provide physical data demonstrating the importance and relationship of these variables to pavement performance. The test section work performed over the past 17 years provides an excellent basis for the additional information needed. However, this previous work is oftentimes incomplete, in that properties and variables — such as the geosynthetic and geosynthetic-base aggregate interaction properties — were not reported.

Given the time and expense associated with the construction and evaluation of test sections, and the inability to explicitly examine the influence of single variables on overall pavement performance, the development of a numerical model should be performed in concert with the evaluation of tests sections. The numerical model should be sufficiently comprehensive to account for the many material properties believed to influence the problem. This model should do more than just describe the dynamic response of the system to a single cycle of applied load. Both test section work and previous work with numerical models has shown the difficulty of describing long-term performance benefit from the first cycle of load application to a pavement. In addition, the model will be incapable of predicting reinforced pavement performance if the model's materials are based on linear layered elastic theory. State-of-the-art constitutive models will be necessary for the aggregate and subgrade soils to allow for the accumulation of permanent strain with increased applied load cycles. Geosynthetic material models must be formulated to allow for a description of the properties outlined in item 1 above. This will probably necessitate the use of elastic-plastic-creep models that allow for direction-dependent material properties. A robust contact model will be necessary to describe shear-interaction between the geosynthetic and surrounding base (or subbase) aggregate.

Such a model can then be used to examine the importance of many variables in a cost-effective and scientifically reproducible fashion. Such a model can also be used to examine item 12, by incorporating appropriate routines to model a true moving wheel load. Large-scale pavement test sections subject to a moving wheel load should be conducted to validate results from the model.

Such a model has the capacity to examine geosynthetic properties that may not currently exist for any manufactured product. The model can be used to develop a set of material properties for a geosynthetic that gives optimal performance. This information can potentially be used by geosynthetic manufacturers to create a product, or perhaps a product line, that is best suited for this application and the various conditions expected for this application.

The combination of additional experimental work and numerical modeling work will permit the development of a design procedure expressed in terms of generic material properties pertinent to this application. The development of new material testing protocols may be necessary to provide for some of the properties identified through this work.

[BLANK]

11.0 CONCLUSIONS

Geosynthetic reinforcement in pavement design and construction should be widespread. Geosynthetic reinforcements are incorporated into permanent, paved roads either as base (or subbase) reinforcement — in flexible pavements to aid in the support of vehicular loads over the life of the pavement; or as subgrade restraint for construction of flexible or rigid roadways over weak subgrade conditions to aid in support of equipment loads on the unpaved base, or subbase, course during construction. Clearly, both base reinforcement and subgrade restraint with geosynthetics are proven techniques for use in pavement design and construction.

The use of geosynthetics to reinforce the aggregate base course of flexible pavement structures has been researched by many groups, including manufacturers, universities, government agencies, etc. It is well documented that certain reinforcements provide substantial load-carrying benefits, within limits. Limits of applicability are defined by subgrade strength, aggregate characteristics, design requirements, and geosynthetic characteristics.

Substantial value-added benefit is achieved with incorporation of geosynthetic reinforcement, within the limits of applicability. Subgrade restraint/stabilization applications are usually more cost effective than other construction options, and the cost effectiveness is often demonstrated by examining initial construction costs with the various options. The cost effectiveness of base reinforcement applications should be examined with a life-cycle cost analysis. Substantial savings can be realized for some agencies or projects, but base reinforcement will not be cost effective for all agencies or projects. The many variables input into a life-cycle cost analysis require an agency-specific, or project-specific, analysis to quantify cost savings.

Various procedures for both base reinforcement design and subgrade restraint design are available. Some procedures use product-specific input and others use generic material properties. Thus, the design procedure dictates the specification approach. Designs based upon generic material properties should use a generic material specification approach. Designs based upon product-specific input should use an approved products list, and should have equivalency defined in terms of performance requirements. Agency recognition that an approved products list is an appropriate specification method for base reinforcement (and some subgrade restraint) is important to successful pavement design with geosynthetic reinforcements.

[BLANK]

REFERENCES

AASHTO, 1997, *Standard Specifications for Geotextiles - M 288*, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 18^{th} Edition, American Association of State Transportation and Highway Officials, Washington, DC.

AASHTO, 1993, *AASHTO Guide for Design of Pavement Structures*, Washington, DC.

AASHTO, 1990, Task Force 25 Report — Guide Specifications and Test Procedures for Geotextiles, Subcommittee on New Highway Materials, American Association of State Transportation and Highway Officials, Washington, DC.

AASHTO, 1972, *Interim Guide for the Design of Pavement Structures*, American Association of State Transportation and Highway Officials, Washington, DC.

Akzo Nobel Geosynthetics, 1998, *TRC-Grid, The backbone of your road structure — Design & Installation Guide*, The Netherlands, 24 p.

Al-Qadi, I.L., Coree, B.J., Brandon, T.L., Bhutta, S.A. and Appea, A.K., 1998, "Quantifying the Separation Characteristic of Geosynthetics in Flexible Pavements," *Proceedings of the Sixth International Conference on Geosynthetics*, Atlanta, GA, USA, Vol. 2, pp. 945-950.

Al-Qadi, I.L., Brandon, T.L. and Bhutta, A., 1997, "Geosynthetic Stabilized Flexible Pavements," *Proceedings of the Conference Geosynthetics '97*, Long Beach, CA, USA, March, Vol. 2, pp. 647-662.

Al-Qadi, I.L., Brandon, T.L., Valentine, R.J., Lacina, B.A. and Smith, T.E., 1994, "Laboratory Evaluation of Geosynthetic Reinforced Pavement Sections," In *Transportation Research Record 1439*, TRB, National Research Council, Washington DC., pp. 25-31.

Anderson, P. and Killeavy, M., 1989, "Geotextiles and Geogrids: Cost Effective Alternate Materials for Pavement Design and Construction," *Proceedings of the Conference Geosynthetics '89*, San Diego, CA, USA, pp. 353-360.

Appea, A.K., Al-Qadi, I.L., Bhutta, S.A. and Coree, B.J., 1998, "Quantitative Assessment of Transition Layer in Flexible Pavements," *Transportation Research Board*, Paper Preprint 980994, presented at TRB, Washington, DC, USA, January.

ASTM, 1998, *Annual Books of ASTM Standards*, West Conshohocken, PA.

Barker, W.R., 1987, *Open-Graded Bases for Airfield Pavements*, Technical Report GL-87-16, USAE Waterways Experiment Station, Vicksburg, MS, USA, 76 p.

Barksdale, R. D., Brown, S. F. and Chan, F., 1989, *Potential Benefits of Geosynthetics in Flexible Pavement Systems*, National Cooperative Highway Research Program Report No. 315, Transportation Research Board, National Research Council, Washington, DC.

Bearden, J.B. and Labuz, J.F., 1998, *Fabric for Reinforcement and Separation in Unpaved Roads*, Minnesota Department of Transportation, Saint Paul, MN, USA, 127 p.

Bender, D.A. and Barenberg, E.J., 1980, "Design and Behavior of Soil-Fabric-Aggregate Systems," In *Transportation Research Record 671*, TRB, National Research Council, Washington, DC, USA, pp. 64-75.

Bhutta, S.A., Al-Qadi, I.L and Brandon, T.L. 1998, "In-Situ Measurements of Flexible Pavement's Response to Vehicular Loading," *Transportation Research Board*, Paper Preprint 980993, presented at TRB, Washington, DC, USA, January, 1998.

Black, P.J. and Holtz, R.D., 1997, *Performance of Geotextile Separators: Bucoda Test Site — Phase II*, Washington State Department of Transportation Report WA-RD 440.1, 210 p.

Brandon, T.L., Al-Qadi, I.L., Lacina, B.A. and Bhutta, S.A., 1996, "Construction and Instrumentation of Geosynthetically Stabilized Secondary Road Test Sections," *Transportation Research Board*, Paper Preprint 960937, presented at TRB, Washington, DC, USA, January, 1996.

Brandon, T.L., Al-Qadi, I.L., Hoffman, S.E., Lacina, B.A., Scarlett, M.J., Weisz, D.E. and Bhutta, S.A., 1995, *Field Testing of Geosynthetically Stabilized Pavement Sections*, Progress report, Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 48 p.

Brown, S.F., Jones, C.P.D. and Brodrick, B.V., 1983, "Discussion of Paper: Use of Non-Woven Fabrics in Permanent Road Pavements," *Proceedings of the Institution of Civil Engineers*, London, UK, Part 2, Vol.75, pp. 343-358.

Brown, S.F., Jones, C.P.D. and Brodrick, B.V., 1982, "Use of Non-Woven Fabrics in Permanent Road Pavements," *Proceedings of the Institution of Civil Engineers*, London, UK, Part 2, Vol.73, pp. 541-563.

Cancelli, A. And Montanelli, F., 1999, "In-Ground Test For Geosynthetic Reinforced Flexible Paved Roads," *Proceedings of the Conference Geosynthetics '99*, Boston, MA, USA, Vol. 2, pp. 863-878.

Cancelli, A., Montanelli, F., Rimoldi, P. and Zhao, A., 1996, "Full Scale Laboratory Testing on Geosynthetics Reinforced Paved Roads," Proceedings of the International Symposium on Earth Reinforcement, Fukuoka/Kyushu, Japan, November, Balkema, pp. 573-578.

Carroll, R.G. Jr., Walls, J.C. and Haas, R., 1987, "Granular Base Reinforcement of Flexible Pavements Using Geogrids," *Proceedings of the Conference Geosynthetics '87*, New Orleans, LA, USA, pp.46-57.

Cedergren, H.R.,1989, <u>Seepage, Drainage, and Flow Nets</u>, Third Edition, John Wiley and Sons, New York, NY, 465 p.

Chan, F.W.K., 1990, *Permanent Deformation Resistance of Granular Layers in Pavements*, Ph.D. Thesis, University of Nottingham, 146 p.

Chan, F.W.K., Barksdale, R.D. and Brown, S.F., 1989, "Aggregate Base Reinforcement of Surfaced Pavements," *Geotextiles and Geomembranes*, Elsevier Applied Science, Oxford, UK, Vol. 8, pp. 165-189.

Christopher, B.R. and Holtz, R.G., 1985, *Geotextile Engineering Manual*, U.S. Department of Transportation, Federal Highway Administration, FHWA-TS-86/203, Washington, DC, USA, 1044 p.

Collin, J. G., Kinney, T. C. and Fu, X., 1996, "Full Scale Highway Load Test of Flexible Pavement Systems with Geogrid Reinforced Base Courses," *Geosynthetics Intentional*, Industrial Fabrics Association International, Roseville, MN, Vol. 3, No. 4, pp. 537-549.

Douglas, R.A., 1993, "Stiffnesses of Geosynthetic Built Unpaved Road Structures: Experimental Programme, Analysis and Results," *Proceedings of the Conference Geosynthetics '93*, Vancouver, BC, pp. 21-34.

Fetten, C.P. and Humphrey, D.N., 1998, *Instrumentation and Performance of Geosynthetics Beneath Flexible Pavements in Winterfort and Frankfort, Maine*, Department of Civil and Environmental Engineering Report, University of Maine, 137 p.

Giroud, J.P., Ah-Line, C. and Bonaparte, R., 1984, "Design of Unpaved Roads and Trafficked Areas with Geogrids," *Polymer Grid Reinforcement*, Thomas Telford, London, UK, pp. 116-127.

Giroud, J.P. and Noiray, L., 1981, "Geotextile Reinforced Unpaved Road Design," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 107, No GT9, pp. 1233-1254.

GMA, 1999, *Geosynthetics in Pavement Systems Applications, Section One: Geogrids, Section Two: Geotextiles*, prepared for AASHTO, Geosynthetics Materials Association, Roseville, MN, 46 p.

GRI, 1998, *GRI Test Methods & Standards*, Geosynthetic Research Institute, Drexel University, Philadelphia, PA.

Haas R., Wall, J., and Carroll, R.G., 1988, "Geogrid Reinforcement of Granular Bases in Flexible Pavements," In *Transportation Research Record 1188*, TRB, National Research Council, Washington, DC, USA, pp. 19-27.

Haliburton, T.A. and Barron, J.V., 1983, "Optimum-Depth Method for Design of Fabric-Reinforced Unsurfaced Roads," Transportation Research Record 916, TRB, National Research Council, Washington, DC, USA, pp. 26-32.

Haliburton, Lawmaster and King, 1970, *Potential Use of Geotextile Fabric in Airfield Runway Design*, Air Force Office of Scientific Research, AFOSR Report 79-00871.

Halliday, A.R. and Potter, J.F., 1984, "The Performance of a Flexible Pavement Constructed on a Strong Fabric," Transport and Road Research Laboratory, Report 1123, Crowthorne, Berkshire, 15 p.

Hayden, S.A., Humphrey, D.N, Christopher, B.R., Henry, K.S. and Fetten, C., 1999, "Effectiveness of Geosynthetics for Roadway Construction in Cold Regions: Results of a Multi-Use Test Section," Proceedings of the Conference Geosynthetics '99, Boston, MA, USA, Vol. 2, pp. 847-862.

Holtz, R.D., Christopher, B.R. and Berg, R.R., [Technical Consultant - DiMaggio, J.A.] 1998, *Geosynthetic Design and Construction Guidelines*, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, FHWA-HI-98-038, 460 p. ALSO AVAILABLE AS: Holtz, R.D., Christopher, B.R. and Berg, R.R., *Geosynthetic Engineering*, BiTech Publishers Ltd., Richmond, BC, Canada, ISBN 0-921095-20-1, 1997, 452 p.

Holtz, R.D. and Sivakugan, N., 1987, "Design Charts for Roads with Geotextiles," *Geotextiles and Geomembranes*, Vol. 5, No. 3, pp. 191-199.

Holtz, R.D., Christopher, B. R. and Berg, R.R., 1995, *Geosynthetic Design and Construction Guidelines*, U.S. Department of Transportation, Federal Highway Administration, FHWA-A-HI-95, National Highway Institute Course No. 13213, Washington, DC, 396 p.

Houlsby, G.T. and Jewell, R.A., 1990, "Design of Reinforced Unpaved Roads for Small Rut Depths," *Proceedings of the 4th International Conference on Geotextiles, Geomembranes and Related Products*, The Hague, Netherlands, Vol. 1, pp. 171-176.

Huntington, G. and Ksaibati, K., 1999, "Evaluation of Geogrid-Reinforced Granular Base," *Geotechnical Special Publication No. 89, Recent Advances in the Characterization of Transportation Geo-Materials*, ASCE, pp. 13-24.

Kennepohl, G., Kamel, N., Walls, J. and Haas, R., 1985, "Geogrid Reinforcement of Flexible Pavements: Design Basis and Field Trials," *Proceedings of the Association of Asphalt Paving Technologists*, San Antonio, TX, February, Vol. 54, pp.45-70.

Kinney, T.C., 1999, "Laboratory Tests to Determine the Direction of Movement of Particles on a Horizontal Plane in a Road During Loading," *Proceedings of the Conference Geosynthetics '99*, Boston, MA, USA, Vol. 1, pp. 279-290.

Kinney, T.C., Stone, D.K. and Schuler, J., 1998a, "Using Geogrids for Base Reinforcement as Measured by Falling Weight Deflectometer in Full-Scale Laboratory Study," *Transportation Research Record 1611*, Washington, DC, pp. 70-77.

Kinney, T.C., Abbott, J. and Schuler, J., 1998b, "Benefits of Using Geogrids for Base Reinforcement with Regard to Rutting," *Transportation Research Record 1611*, Washington, DC, pp. 86-96.

Kinney, T.C. and Xiaolin, Y., 1995, "Geogrid Aperture Rigidity by In-Plane Rotation," *Proceedings of the Conference Geosynthetics '95*, Nashville, TN, USA, Vol. 2, pp. 525-538.

Kinney, T.C. and Barenberg, E.J., 1982, "The Strengthening Effect of Geotextiles on Soil-Geotextile-Aggregate Systems," *Proceedings of the Second International Conference on Geotextiles*, Las Vegas, NV, USA, Vol. 2, pp. 347-352.

Koerner, R.M., Designing With Geosynthetics, 4th Edition, Prentice-Hall Inc., Englewood Cliffs, NJ, 1998, 761 p.

Laguros, J.G. and Miller, G.A., 1997, *Stabilization of Existing Subgrades to Improve Constructibility During Interstate Pavement Reconstruction,* National Cooperative Highway Research Program, Synthesis of Highway Practice 247, Transportation Research Board, National Academy Press, Washington, D.C., 1997, 75 p.

Means, 1990, *Means Heavy Construction Cost Data*, R.S. Means Company, Kingston, MA.

Milligan, G.W.E. and Love, J.P., 1985, "Model Testing of Geogrids Under an Aggregate Layer on Soft Ground," Symposium on Polymer Grid Reinforcement, Thomas Telford Limited, London, UK, pp. 128-138.

Mirafi, 1982, *Guidelines for Design of Flexible Pavements Using Mirafi Woven Geotextiles*, TC Mirafi, Pendergrass, GA, 23 p.

Miura, N., Sakai, A., Taesiri, Y., Yamanouchi, T. and Yasuhara, K., 1990, "Polymer Grid Reinforced Pavement on Soft Clay Grounds," *Geotextiles and Geomembranes*, Elsevier Applied Science, Oxford, UK, Vol. 9, pp. 99-123.

Moghaddas-Nejad, F. and Small, J.C., 1996, "Effect of Geogrid Reinforcement in Model Track Tests on Pavements," *Journal of Transportation Engineering*, ASCE, Vol. 122, No. 6, pp. 468-474.

Montanelli, F., Zhao, A. and Rimoldi, P., 1997, "Geosynthetic-Reinforced Pavement System: Testing and Design," *Proceedings of the Conference Geosynthetics '97*, Long Beach, CA, USA, Vol. 2, pp. 619-632.

Penner, R., 1985, *Geogrid Reinforcement of the Granular Base Layer in Conventional Three-Layer Pavement Sections*, M.S. Thesis, University of Waterloo, August, 130 p.

Penner, R., Haas, R., Walls, J. and Kennepohl, G., 1985, "Geogrid Reinforcement of Granular Bases," Paper Presented at the *Roads and Transportation Association of Canada Annual Conference*, Vancouver, Canada, September.

Perkins, S.W., 1999a, "Mechanical Response of Geosynthetic Reinforced Pavements," *Geosynthetics International*, Industrial Fabrics Association International, Roseville, MN, In-Review.

Perkins, S.W., 1999b, *Geosynthetic Reinforcement of Flexible Pavements: Laboratory Based Pavement Test Sections*, Federal Highway Administration Report FHWA/MT-99-001/8138, Montana Department of Transportation, 140 p.

Perkins, S.W., Ismeik, M. and Fogelsong, M.L., 1999, "Influence of Geosynthetic Placement Position on the Performance of Reinforced Flexible Pavement Systems," *Proceedings of the Conference Geosynthetics '99*, Boston, MA, USA, Vol. 1, pp. 253-264.

Perkins, S.W., Ismeik, M. and Fogelsong, M.L., 1998a, "Mechanical Response of a Geosynthetic-Reinforced Pavement System to Cyclic Loading," *Proceedings of the Fifth International Conference on the Bearing Capacity of Roads and Airfields*, Trondheim, Norway, Vol. 3, pp. 1503-1512.

Perkins, S.W., Ismeik, M., Fogelsong, M.L., Wang, Y., Cuelho, E.V., 1998b, *Proceedings of the Sixth International Conference on Geosynthetics*, "Geosynthetic-Reinforced Pavements: Overview and Preliminary Results," Atlanta, GA, March, 1998, Vol.2, pp. 951-958.

Perkins, S.W. and Ismeik, M., 1997a, "A Synthesis and Evaluation of Geosynthetic Reinforced Base Course Layers in Flexible Pavements: Part I Experimental Work," *Geosynthetics International,* Vol. 4, No. 6, pp. 549-604.

Perkins, S.W. and Ismeik, M., 1997b, "A Synthesis and Evaluation of Geosynthetic Reinforced Base Course Layers in Flexible Pavements: Part II Analytical Work," *Geosynthetics International,* Vol. 4, No. 6, pp. 605-621.

Richardson, G.N., 1997, "Geogrids vs. Geotextiles in Roadway Applications", *Geotechnical Fabrics Report*, Industrial Fabrics Association International, Roseville, MN, October-November, pp. 13-20.

Robnett, Q.L., Lai, J.S., Lavin, J.G., Murch, L.E. and Murray, C.D., 1980, "Use of Geotextiles in Road Construction: An Experimental Study," Preprints of Papers to be Presented at the First Canadian Symposium on Geotextiles, Canadian Geotechnical Society, Calgary, Alberta, Canada, pp. 113-124.

Ruddock, E.C., Potter, J.F. and McAvoy, A.R., 1982, "A Full-Scale Experiment on Granular and Bituminous Road

Pavements Laid on Fabrics," *Proceedings of the Second International Conference on Geotextiles*, Las Vegas, NV, USA, Vol. 2, pp. 365-370.

Sellmeijer, J.B., 1990, "Design of Geotextile Reinforced Paved Roads and Parking Areas," *Proceedings of the Fourth International Conference on Geotextiles, Geomembranes and Related Products*, The Hague, The Netherlands, Balkema, Vol. 1, pp. 177-182.

Smith, T.E., Brandon, T.L., Al-Qadi, I.L., Lacina, B.A., Bhutta, S.A. and Hoffman, S.E., 1995, *Laboratory Behavior of Geogrid and Geotextile Reinforced Flexible Pavements*, Final Report Submitted to Atlantic Construction Fabrics, Inc. Amoco Fibers and Fabrics Company and the Virginia Center for Innovative Technology, February, Virginia Polytechnic Institute and State University, Department of Civil Engineering, Blacksburg, VA, USA, 94 p.

Steward, J.E., Williamson, R. and Mohney, J., 1977, "Guidelines for Use of Fabrics in Construction and Maintenance of Low-Volume Roads," USDA, Forest Service Report PB-276 972, Portland, OR, 172 p.

Tensar, 1996, *Tensar Technical Note: BR96, Design Guideline for Flexible Pavements with Tensar Geogrid Reinforced Base Layers*, The Tensar Corporation, Atlanta, GA, 109 p.

U.S. Army Corps of Engineers, 1999, *Chemical Demilitarization Alternative Technology Program (ALT-TECH), Aberdeen Proving Grounds, (Edgewood Area) Maryland, Test Strip Pilot Study,* U.S. Army Engineer District - Baltimore, Engineering Division, Geotechnical & Water Resources Branch, 93 p .

Webster, S. L., 1993, *Geogrid Reinforced Base Courses for Flexible Pavements for Light Aircraft, Test Section Construction, Behavior Under Traffic, Laboratory Tests, and Design Criteria*, Technical Report GL-93-6, USAE Waterways Experiment Station, Vicksburg, MS, USA, 86 p.

Webster, S. L., 1992, *Geogrid Reinforced Base Courses for Flexible Pavements for Light Aircraft: Literature Review and Test Section Design*, Technical Report GL-92-6, USAE Waterways Experiment Station, Vicksburg, MS, USA, 33 p.

White, D.W. Jr., 1991, *Literature Review on Geotextiles to Improve Pavements for General Aviation Airports*, Technical Report GL-91-3, USACE Waterways Experiment Station, Vicksburg, MS, USA, 58 p.

Zhao, A. and Foxworthy, P.T., 1999, Geogrid Reinforcement of Flexible Pavements: A Practical Perspective, *Geotechnical Fabrics Report*, Vol. 17, No. 4, May, Industrial Fabrics Association International, Roseville, MN, pp. 28-34.

APPENDIX A — SEPARATION AND STABILIZATION[1]

A.1 INTRODUCTION

Geosynthetics offer significant potential benefit when used in roadway systems. Geotextiles increase stability and improve performance of weak subgrade soils primarily by separating the aggregate from the subgrade. In addition, geogrids and some geotextiles can provide strength through friction or interlock developed between the aggregate and the geosynthetic. Geotextiles can also provide filtration and drainage by allowing excess pore water pressures in the subgrade to dissipate into the aggregate base course and, in cases of poor-quality aggregate, through the geotextile plane itself.

Simply incorporating a relatively low cost geotextile (estimated at less than 5% of the pavement system cost) can as a minimum provide assurance that the original design will be maintained throughout the life of the system such that the original estimated design life (without the geosynthetic) is achieved. This benefit alone could justify the cost of the geosynthetic for agencies whose current designs fail prematurely, however the real value comes with a roadway life that is extended beyond the original anticipated design. Typically if the road will last one to two years longer than it would have without the geosynthetic, there is a payback from using the geosynthetic. However, based on a review of the literature, roads incorporating simple geosynthetic separators have been found to increase roadway design life as much as 50% or more. With the advent of reinforcement, even greater benefits are possible as indicated by the literature review in the previous section. The actual benefits will depend on the actual function(s) (or mechanisms) that the geosynthetic is performing in the specific applications. The functions will vary depending on whether the application is for a temporary or permanent road, whether it is paved of unpaved, and the subgrade conditions.

A.1.1 Functions of Geosynthetics in Roadways

A geosynthetic placed at the interface between the aggregate base course and the subgrade functions as a *separator* to prevent two dissimilar materials (subgrade soils and aggregates) from intermixing. Geotextiles and geogrids perform this function by preventing penetration of the aggregate into the subgrade (localized bearing failures) (Figure A-1). In addition, geotextiles prevent intrusion of subgrade soils up into the base course aggregate. Localized bearing failures and subgrade intrusion only occur in very soft, wet, weak subgrades. It only takes a small amount of fines to significantly

[1] Holtz, R.D., Christopher, B.R. and Berg, R.R., [Technical Consultant - DiMaggio, J.A.], *Geosynthetic Design and Construction Guidelines*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., FHWA-HI-98-038, 1998, 460 p. {Also available as: Holtz, R.D., Christopher, B.R. and Berg, R.R., *Geosynthetic Engineering*, BiTech Publishers Ltd., Richmond, British Columbia, Canada, ISBN 0-921095-20-1, 452 p.}

reduce the friction angle of select granular aggregate. Therefore, separation is important to maintain the design thickness and the stability and load-carrying capacity of the base course. Soft subgrade soils are most susceptible to disturbance during construction

Figure A-1. Concept of geotextile separation in roadways (after Rankilor, 1981).

activities such as clearing, grubbing, and initial aggregate placement. Geosynthetics can help minimize subgrade disturbance and prevent loss of aggregate during construction. Thus, the primary function of the geotextile in this application is separation, and can in some cases be considered a secondary function for geogrids.

The system performance may also be influenced by secondary functions of **filtration**, **drainage**, and **reinforcement**. The geotextile acts as a filter to prevent fines from migrating up into the aggregate due to high pore water pressures induced by dynamic wheel loads. It also acts as a drain, allowing the excess pore pressures to dissipate through the geotextile and the subgrade soils to gain strength through consolidation and improve with time.

Geogrids and geotextiles provide reinforcement through three possible mechanisms.

1. *Lateral restraint of the base and subgrade* through friction and interlock between the aggregate, soil and the geosynthetic (Figure A-2a).
2. *Increase in the system bearing capacity* by forcing the potential bearing capacity failure

surface to develop along alternate, higher shear strength surfaces (Figure A-2b).

3. *Membrane support* of the wheel loads (Figure A-2c).

When an aggregate layer is loaded by a wheel or track, the aggregate tends to move or shove laterally, as shown in Figure A-2a, unless it is restrained by the subgrade or geosynthetic reinforcement. Soft, weak subgrade soils provide very little lateral restraint, so when the aggregate moves laterally, ruts develop on the aggregate surface and also in the subgrade. A geogrid with good interlocking capabilities or a geotextile with good frictional capabilities can provide tensile resistance to lateral aggregate movement. Another possible geosynthetic reinforcement mechanism is illustrated in Figure A-2b. Using the analogy of a wheel load to a footing, the geosynthetic reinforcement forces the potential bearing capacity failure surface to follow an alternate higher strength path. This tends to increase the bearing capacity of the roadway.

A third possible geosynthetic reinforcement function is membrane-type support of wheel loads, as shown conceptually in Figure A-2c. In this case, the wheel load stresses must be great enough to cause plastic deformation and ruts in the subgrade. If the geosynthetic has a sufficiently high tensile modulus, tensile stresses will develop in the reinforcement, and the vertical component of this membrane stress will help support the applied wheel loads. As tensile stress within the geosynthetic cannot be developed without some elongation, wheel path rutting (in excess of 100 mm) is required to develop membrane-type support. Therefore, this mechanism is generally limited to temporary roads or the first aggregate lift in permanent roadways.

A.1.2 Subgrade Conditions in which Geosynthetics are Most Useful

Geotextile separators have a 20+ year history of successful use for the stabilization of very soft wet subgrades. Based on experience and several case histories summarized by Haliburton, Lawmaster, and McGuffey (1981) and Christopher and Holtz (1985), the following subgrade conditions are considered to be the most appropriate for geosynthetic use in roadway construction:

- Poor soils
  - (USCS: SC, CL, CH, ML, MH, OL, OH, and PT)
  - (AASHTO: A-5, A-6, A-7-5, and A-7-6)
- Low undrained shear strength
  - $\tau_f = c_u < 90$ kPa
  - CBR < 3 {Note: CBR as determined with ASTM D 4429 Bearing $M_R \approx 30$ MPa Ratio of Soils in Place}
- High water table
- High sensitivity

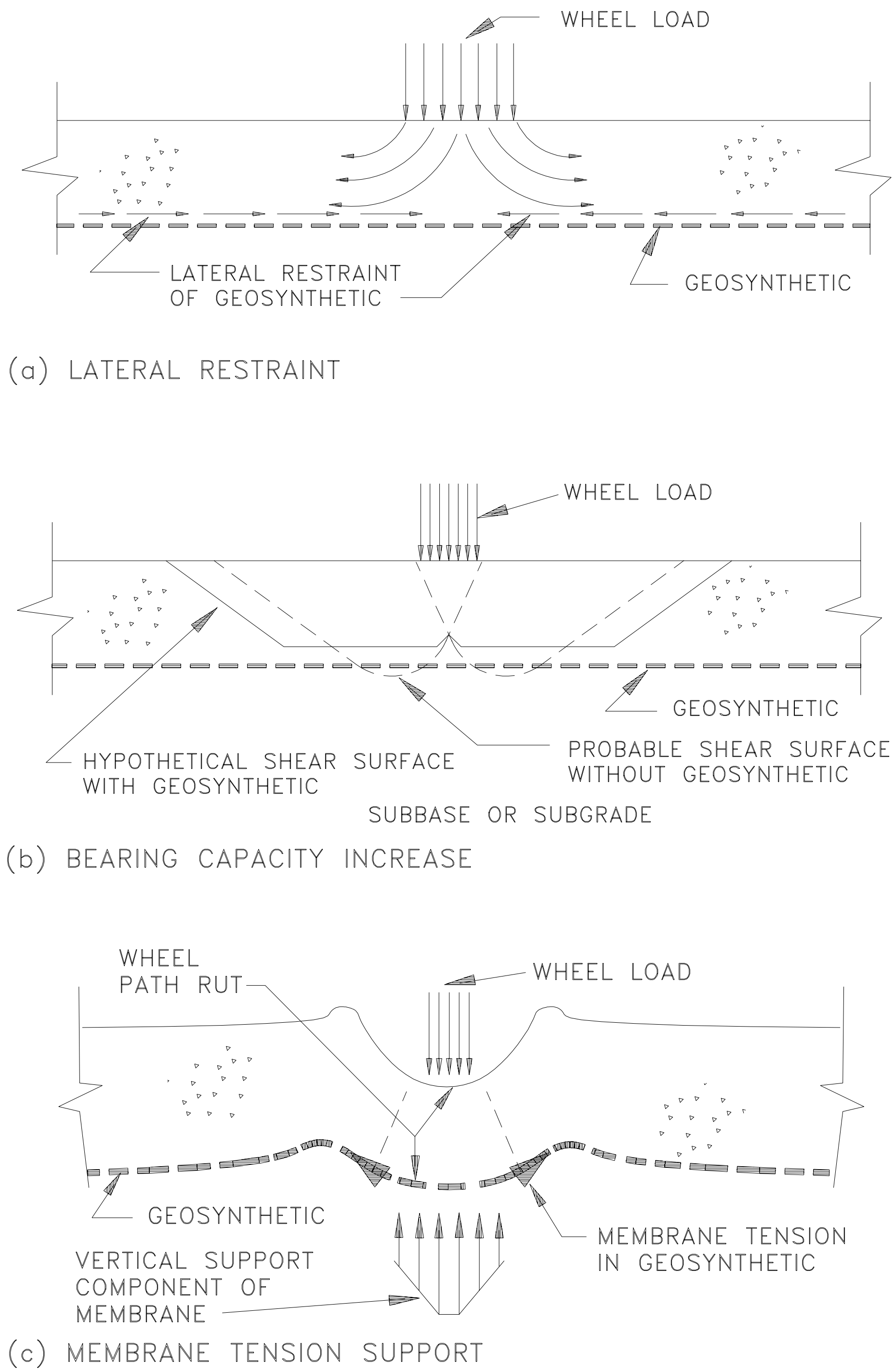


Figure A-2. Possible reinforcement functions provided by geosynthetics in roadways: (a) lateral restraint, (b) bearing capacity increase, and (c) membrane tension support (after Haliburton, et al., 1981).

Under these conditions, geosynthetics function primarily as separators and filters to stabilize the subgrade, improving construction conditions and allowing long-term strength improvements in the subgrade. If large ruts develop during placement of the first aggregate lift, then some reinforcing effect is also present. As a summary recommendation, the following geotextile functions are appropriate for the corresponding subgrade strengths:

Undrained Shear Strength (kPa)	Subgrade CBR	Functions
60 - 90	2 - 3	Filtration and possibly separation
30 - 60	1 - 2	Filtration, separation, and possibly reinforcement
< 30	< 1	All functions, including reinforcement

This table implicates that geotextiles do not provide a useful function when the undrained shear strength is greater than about 90 kPa (CBR about 3). From a foundation engineering point of view, clay soils with undrained shear strengths of 90 kPa are considered to be stiff clays (Terzaghi and Peck, 1967, p. 30) and are generally quite good foundation materials. Allowable footing pressures on such soils equal 150 kPa or greater. Simple stress distribution calculations show that for **static** loads, such soils will readily support reasonable truck loads and tire pressures, even under relatively thin granular bases.

Dynamic loads and high tire pressures are another matter. Some rutting will probably occur in such soils, especially after a few hundred passes (Webster, 1993). If traffic is limited, as it is in many temporary roads, or if shallow (< 75 mm) ruts are acceptable, as in most construction operations, then a maximum undrained shear strength of about 90 kPa (CBR = 3) for geosynthetic use in highway construction seems reasonable.

An exception to this is in permeable base applications. Even on firm to firmer subgrades, a geotextile placed beneath the base functions as a separator and filter, as illustrated in Figure A-3.

A.2 APPLICATIONS

A.2.1 Temporary and Permanent Roads

Roads and highways are broadly classified into two categories: permanent and temporary, depending on their service life, traffic applications, or desired performance. Permanent roads include both paved and unpaved systems, which usually remain in service 10 years or more. Permanent roads may be subjected to more than a million load applications during their design lives. On the other hand, temporary roads are, in most cases, unpaved. They remain in service for only short periods of time (often less than 1 year), and are usually subjected to fewer than 10,000 load applications during their services lives. Temporary roads include detours, haul and access roads, construction platforms, and

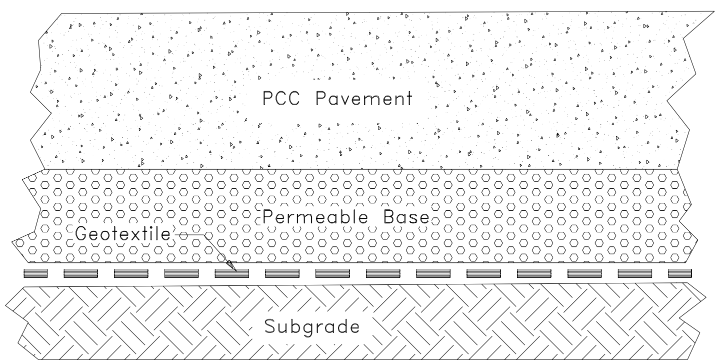


Figure A-3. Geotextile separator beneath permeable base (Baumgartner, 1994).

stabilized working *tables* required for the construction of permanent roads, as well as embankments over soft foundations.

Geosynthetics allow construction equipment access to sites where the soils are normally too weak to support the initial construction work. This is one of the more important uses of geosynthetics. Even if the finished roadway can be supported by the subgrade, it may be virtually impossible to begin construction of the embankment or roadway. Such sites require stabilization by dewatering, demucking, excavation and replacement with select granular materials, utilization of stabilization aggregate, chemical stabilization, etc. Geosynthetics can often be a cost-effective alternate to these expensive foundation treatment procedures.

Furthermore, geosynthetics enable contractors to meet minimum compaction specifications for the first two or three aggregate lifts. This is especially true on very soft, wet subgrades, where the use of ordinary compaction equipment is very difficult or even impossible. Long term, a geosynthetic acts to maintain the roadway design section and the base course material integrity. Thus, the geosynthetic will ultimately increase the life of the roadway, whether temporary or permanent.

A.2.2 Permanent Roads

Permanent road design essentially consists of selecting structural elements (the pavement surface, the base and the subbase) that will reduce the stress at the subgrade to support the anticipated traffic over the anticipated design life of the system. If any of the components fails prematurely, the design life will not be achieved.

Yoder and Witczak (1975) define two types of pavement distress, or failure. The first is a structural failure, in which a collapse of the entire structure or a breakdown of one or more of the pavement components renders the pavement incapable of sustaining the loads imposed on its surface. The second type failure is a functional failure; it occurs when the pavement, due to its roughness, is unable to carry out its intended function without causing discomfort to drivers or passengers or imposing high stresses on vehicles. The cause of these failure conditions may be due to excessive loads, climatic and environmental conditions, poor drainage leading to poor subgrade conditions, and disintegration of the component materials. Excessive loads, excessive repetition of loads, and high tire pressures can cause either structural or functional failures.

Pavement failures may occur due to the intrusion of subgrade soils into the granular base, which results in inadequate drainage and reduced stability. Distress may also occur due to excessive loads that cause a shear failure in the subgrade, base course, or the surface. Other causes of failures are surface fatigue and excessive settlement, especially differential of the subgrade. Volume change of subgrade soils due to wetting and drying, freezing and thawing, or improper drainage may also cause pavement distress. Inadequate drainage of water from the base and subgrade is a major cause of pavement problems (Cedergren, 1989). If the subgrade is saturated, excess pore pressures will develop under traffic loads, resulting in subsequent softening of the subgrade.

Improper construction practices may also cause pavement distress. Wetting of the subgrade during construction may permit water accumulation and subsequent softening of the subgrade in the rutted areas after construction is completed. Use of dirty aggregates or contamination of the base aggregates during construction may produce inadequate drainage, instability, and frost susceptibility. Reduction in design thickness during construction due to insufficient subgrade preparation may result in undulating subgrade surfaces, failure to place proper layer thicknesses, and unanticipated loss of base materials due to subgrade intrusion. Yoder and Witczak (1975) state that a major cause of pavement deterioration is inadequate observation and field control by qualified engineers and technicians during construction.

After construction is complete, improper or inadequate maintenance may also result in pavement distress. Sealing of cracks and joints at proper intervals must be performed to prevent surface water infiltration. Maintenance of shoulders will also affect pavement performance.

Properly designed geosynthetics can enhance pavement performance and reduce the likelihood of failures.

A.2.3 Summary of Potential Benefits

The Federal Highway Administration has identified the following benefits of using geosynthetics in roadways:

1. Reducing the intensity of stress on the subgrade and preventing the base aggregate from penetrating into the subgrade (function: separation).
2. Preventing subgrade fines from pumping or otherwise migrating up into the base (function: separation and filtration).
3. Allowing an increase in subgrade strength over time (function: filtration).
4. Reducing the differential settlement of the roadway, which helps maintain pavement integrity and uniformity (function: reinforcement). Geosynthetics will also aid in reducing differential settlement in transition areas from cut to fill. {NOTE: Total and consolidation settlements are not reduced by the use of geosynthetic reinforcement.}
5. Providing capillary breaks to reduce frost action in frost-susceptible soils (function: drainage), and to provide membrane-encapsulated soil layers (MESL) to reduce the effects of seasonal water content changes on roadways on swelling clays.
6. Preventing contamination of the base materials, which may allow more open-graded, free-draining aggregates to be considered in the design (function: filtration).
7. Reducing the depth of excavation required for the removal of unsuitable subgrade materials (function: separation and reinforcement).
8. Reducing the thickness of aggregate required to stabilize the subgrade (function: separation and reinforcement).
9. Reducing disturbance of the subgrade during construction (function: separation and reinforcement).
10. Reducing maintenance and extending the life of the pavement (functions: all).

An optimal benefit that is not included in the above list is the reinforcement of the base or subbase aggregate to either reduce the section or increase the design life to the pavement. It is this benefit, along with the reinforcement benefits identified in 7, 8, and 9 above, that is the focus of this paper.

[BLANK]

APPENDIX B — EXCERPT FROM AASHTO M288 SPECIFICATION, GEOTEXTILE SEPARATION AND STABILIZATION

Excerpt from *Standard Specifications for Transportation Materials and Methods of Sampling and Testing* (1997, AASHTO).

1. SCOPE

1.1 This is a materials specification covering geotextile fabrics for use in . . . ; separation; stabilization; . . . . This is a material purchasing specification and design review of use is recommended.

1.2 This is not a construction or design specification. This specification is based on geotextile survivability from installation stresses. . . .

. . . .

. . . .

. . . .

7. GEOTEXTILE PROPERTY REQUIREMENTS FOR . . . ., SEPARATION, STABILIZATION, AND . . . .

7.1 General Requirements

7.1.1 Table 1 provides strength properties for three geotextile classes. The geotextile shall conform to the properties of Table 1 based on the geotextile class required in Table 2, 3, 4, or 5 for the indicated application.

7.1.2 All numeric values in Table 1 represent MARV in the weaker principal direction. The geotextile properties required for each class are dependent upon geotextile elongation. When sewn seams are required, the seam strength, as measured in accordance with ASTM D 4632, shall be equal to or greater than 90 percent of the specified grab strength.

. . .

7.3 Separation Requirements

7.3.1 Description. This specification is applicable to the use of a geotextile to prevent mixing of a subgrade soil and an aggregate cover material (subbase, base, select embankment, etc.). This specification may also apply to situations other than beneath pavements where separation of two dissimilar materials is required but where water seepage through the geotextile is not a critical function.

7.3.2 The separation application is appropriate for pavement structures constructed over soils with a California Bearing Ratio equal to or greater than 3 (CBR $\geq$ 3) (shear strength greater than approximately 90 kPa). It is appropriate for unsaturated subgrade soils. The primary function of a geotextile in this application is separation.

7.3.3 Geotextile Requirements. The geotextile shall meet the requirements of Table 3. All numeric values in Table 3 except AOS represent MARV in the weakest principal direction. Values for AOS represent maximum average roll values.

7.3.4 The property values in Table 3 represent default values which provide for sufficient geotextile survivability under most construction conditions. Note 1 of Table 3 provides for a reduction in the minimum property requirements when sufficient survivability information is available. The Engineer may also specify properties different from those listed in Table 3 based on engineering design and experience.

7.4 Stabilization Requirements

7.4.1 Description. This specification is applicable to the use of a geotextile in wet, saturated conditions to provide the coincident functions of separation and filtration. In some installations, the geotextile can also provide the function of reinforcement. Stabilization is applicable to pavement structures constructed over soils with a California Bearing Ratio between one and three ($1<CBR<3$) (shear strength between approximately 30 kPa and 90 kPa).

7.4.2 The stabilization application is appropriate for subgrade soils which are saturated due to a high groundwater table or due to prolonged periods of wet weather. This specification is not appropriate for embankment reinforcement where stress conditions may cause global subgrade foundation or stability failure. Reinforcement of the pavement section is a site specific design issue.

7.4.3 Geotextile Requirements. The geotextile shall meet the requirements of Table 4. All numeric values in Table 4 except AOS represent MARV in the weakest principal direction. Values for AOS represent maximum average roll values.

7.4.4 The property values in Table 4 represent default values which provide for sufficient geotextile survivability under most construction conditions. Note 1 of Table 4 provides for a reduction in the minimum property requirements when sufficient survivability information is available. The Engineer may also specify properties different from those listed in Table 3 based on engineering design and experience.

. . . .

. . . .

Table 1. Geotextile Strength Property Requirements

			Geotextile Class[1]					
			Class 1		Class 2		Class 3	
	Test Methods	Units	Elongation < 50%[2]	Elongation ≥ 50%[2]	Elongation < 50%[2]	Elongation ≥ 50%[2]	Elongation < 50%[2]	Elongation ≥ 50%[2]
Grab Strength	ASTM D 4632	N	1400	900	1100	700	800	500
Sewn Seam Strength[3]	ASTM D 4632	N	1260	810	990	630	720	450
Tear Strength	ASTM D 4533	N	500	350	400[4]	250	300	180
Puncture Strength	ASTM D 4833	N	500	350	400	250	300	180
Burst Strength	ASTM D 3786	kPa	3500	1700	2700	1300	2100	950
Permittivity	ASTM D 4491	sec^{-1}	Minimum property values for permittivity, AOS, and UV stability are based on geotextile application. Refer to Table 2 subsurface drainage, Table 3 for separation, Table 4 for stabilization, and Table 5 for permanent erosion control.					
Apparent Opening Size	ASTM D 4751	mm						
Ultraviolet Stability	ASTM D 4355	%						

Property Notes for Table 1

[1] Required geotextile class is designated in Table 2, 3, 4, or 5 for the indicated application. The severity of installation conditions for the application generally dictate the required geotextile class. Class 1 is specified for more severe or harsh installation conditions where there is a greater potential for geotextile damage, and Class 2 and 3 are specified for less severe conditions.

[2] As measured in accordance with ASTM D 4632.

[3] When sewn seams are required. Refer to Appendix for overlap seam requirements.

[4] The required MARV tear strength for woven monofilament geotextiles is 250 N.

Table 3. Separation Geotextile Property Requirements

	Test Methods	Units	Requirements
Geotextile Class			Class 2 from Table 1[1]
Permittivity	ASTM D 4491	sec^{-1}	0.02[2]
Apparent Opening Size	ASTM D 4751	mm	0.60 max. avg. roll value
Ultraviolet Stability (Retained Strength)	ASTM D 4355	%	50% after 500 hrs of exposure

Property Notes for Table 3

[1] Default geotextile selection. The Engineer may specify a Class 3 geotextile from Table 1 based on one or more of the following:

a) The Engineer has found Class 3 geotextiles to have sufficient survivability based on field experience.

b) The Engineer has found class 3 geotextiles to have sufficient survivability based on laboratory testing and visual inspection of a geotextile sample removed from a field test section constructed under anticipated field conditions.

c) Aggregate cover thickness of the first lift over the geotextile exceeds 300 m and the aggregate diameter is less than 50 mm.

[2] Default value. Permittivity of the geotextile should be greater than that of the soil ($\psi_g > \psi_s$). The Engineer may also require the permeability of the geotextile to be greater than that of the soil ($k_g > k_s$).

Table 4. Stabilization Geotextile Property Requirements

	Test Methods	Units	Requirements
Geotextile Class			Class 1 from Table 1[1]
Permittivity	ASTM D 4491	sec^{-1}	0.05[2]
Apparent Opening Size	ASTM D 4751	mm	0.43 max. avg. roll value
Ultraviolet Stability (Retained Strength)	ASTM D 4355	%	50% after 500 hrs of exposure

Property Notes for Table 4

[1] Default geotextile selection. The Engineer may specify a Class 2 or 3 geotextile from Table 1 based on one or more of the following:

a) The Engineer has found the class of geotextile to have sufficient survivability based on field experience.

b) The Engineer has found the class of geotextile to have sufficient survivability based on laboratory testing and visual inspection of a geotextile sample removed from a field test section constructed under anticipated field conditions.

[2] Default value. Permittivity of the geotextile should be greater than that of the soil ($\psi_g > \psi_s$). The Engineer may also require the permeability of the geotextile to be greater than that of the soil ($k_g > k_s$).

APPENDIX C — LIFE-CYCLE COST ANALYSES

Four example life-cycle cost calculations follow. The calculations are based upon 5,000,000 equivalent single axle loads (ESALs) over the analysis period. The first computation is for an unreinforced pavement structure. The unreinforced example provides the basis for comparison of the geosynthetic reinforcement examples. Input parameters used in the example calculations are listed in Table 6-3.

The second computation is a reduced base course thickness. The geosynthetic reinforcement is used to decrease the required aggregate base course thickness. The performance period is extended in the third computation. The geosynthetic reinforcement is used to increase the performance period (i.e., time to rehabilitation), and uses the same base course thickness as the unreinforced example.

The fourth computation combines a base course reduction and extension of the performance periods. The geosynthetic reinforcement is used to increase the performance period (i.e., time to rehabilitation) and to reduce the base course thickness. A summary of the results of the analyses is presented in Table 6-4. The example life-cycle cost analyses were performed with the AASHTO DARWIN™ computer program.

1997 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare
Computer Software Product

Life Cycle Cost Module

Case I - Unreintbrced (500,000 ESAL'S)

Life Cycle Cost Data

Summary

Analysis Period	40 years
Project Length	1.6 km
Discount Rate	3.5 %
Number of Lanes in One Direction	1
Type of Roadway	Undivided

Total Costs – Using NPV on a basis of total costs for one direction

Initial Construction Cost	$146,644
Rehabilitation Cost	$48,124
Salvage Value	$0
Total Cost	$194,768

Initial Construction

Initial construction of pavement

Construction Year	2000
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$146,250.79	$146,250.79
Maintenance	DARWin Calculated	$393.46	$393.46
Total	–	$146,644.25	$146,644.25

Rehabilitation #1

First rehabilitation

Rehabilitation Year	2010
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$21,481.82
Maintenance	DARWin Calculated	$393.46	$278.93
Total	–	$30,695.69	$21,760.75

Rehabilitation #2

Second rehabilitation

Rehabilitation Year	2020
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$15,228.87
Maintenance	DARWin Calculated	$393.46	$197.74
Total	–	$30,695.69	$15,426.61

Rehabilitation #3

Third rehabilitation

Rehabilitation Year	2030
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$10,796.03
Maintenance	DARWin Calculated	$393.46	$140.18
Total		$30,695.69	$10,936.21

Salvage Values

Salvage Year	2040

Cost Information -- Using NPV on a basis of total costs for one direction

Phase	Description	Source	Salvage Value	Net Value
Initial Construction	No salvage value included i	... User Entered	$0.00	$0.00
Rehabilitation #1	No salvage value included i	... User Entered	$0.00	$0.00
Rehabilitation #2	No salvage value included i	... User Entered	$0.00	$0.00
Rehabilitation #3	No salvage value included i	... User Entered	$0.00	$0.00

Initial Construction Maintenance Costs

Year Maintenance Costs Begin	2005
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Rehabilitation #1 Maintenance Costs

Year Maintenance Costs Begin	2015
Annual Maintenance Costs	$62.50 per lane km
Annual Increase 'in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Rehabilitation #2 Maintenance Costs

Year Maintenance Costs Begin	2025
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Rehabilitation #3 Maintenance Costs

Year Maintenance Costs Begin	2035
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Initial Construction Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	499	$19,247.88
ACC Binder	T.L.	2	metric ton	$38.5	840	$32,417.48
Aggregate Base -- crushed stone	T.L.	3	metric ton	$22.04	4,292	$94,585.43

Non Discounted Costs (One Direction)*

Traffic Lane	$146,250.79
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $146,250.79

*Note: These values are not represented by the inputs or an error occurred in calculation.

Rehabilitation #1 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)*

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

*Note: These values are not represented by the inputs or an error occurred in calculation.

Rehabilitation #2 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)*

Tratlic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

*Note: These values are not represented by the inputs or an error occurred in calculation.

Rehabilitation #3 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,73 1.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)*

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

*Note: These values are not represented by the inputs or an error occurred in calculation.

Page 4

Salvage Value Pay Items for Initial Construction

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost

Non Discounted Costs (One Direction)*

Traffic Lane –
Inner Shoulder –
Outer Shoulder –
Miscellaneous –

Total Non Discounted Cost (One Direction) –

*Note: These values are not represented by the inputs or an error occurred in calculation.

Salvage Value Pay Items for Rehabilitation #1

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost

Non Discounted Costs (One Direction)*

Traffic Lane –
Inner Shoulder –
Outer Shoulder –
Miscellaneous –

Total Non Discounted Cost (One Direction) –

*Note: These values are not represented by the inputs or an error occurred in calculation.

Salvage Value Pay Items for Rehabilitation #2

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost

Non Discounted Costs (One Direction)*

Traffic Lane –
Inner Shoulder –
Outer Shoulder –
Miscellaneous –

Total Non Discounted Cost (One Direction) –

*Note: These values are not represented by the inputs or an error occurred in calculation.

Salvage Value Pay Items for Rehabilitation #3

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost

Non Discounted Costs (One Direction)*

Traffic Lane –
Inner Shoulder –
Outer Shoulder –
Miscellaneous –

Total Non Discounted Cost (One Direction) –

*Note: These values are not represented by the inputs or an error occurred in calculation.

Initial Construction -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	38
2	ACC Binder	3.66	64
3	Aggregate Base – crushed stone	3.66	305

Initial Construction -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Initial Construction -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Rehabilitation #1 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #1 Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness – mm

Rehabilitation #1 Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness – mm

Rehabilitation #2 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #2 -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness – mm

Rehabilitation #2 -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness – mm

Rehabilitation #3 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #3 – Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness – mm

Rehabilitation #3 – Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness – mm

1997 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare Computer Software Product
Life Cycle Cost Module
Case 2 – Reduced base course thickness (500,000 ESAL'S)

Life Cycle Cost Data

Summary

Analysis Period	40 years
Project Length	1.6 km
Discount Rate	3.5 %
Number of Lanes in One Direction	1
Type of Roadway	Undivided

Total Costs — Using NPV on a basis of total costs for one direction

Initial Construction Cost	$139,441
Rehabilitation Cost	$48,124
Salvage Value	$0
Total Cost	$187,565

Initial Construction

Initial construction of pavement

Construction Year	2000
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$139,047.74	$139,047.74
Maintenance	DARWin Calculated	$393.46	$393.46
Total		$139,441.20	$139,441.20

Rehabilitation #1

First rehabilitation

Rehabilitation Year	2010
Performance Period	10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$21,481.82
Maintenance	DARWin Calculated	$393.46	$278.93
Total	–	$30,695.69	$21,760.75

Rehabilitation #2

Second rehabilitation

Rehabilitation Year 2020
Performance Period 10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$15,228.87
Maintenance	DARWin Calculated	$393.46	$197.74
Total	–	$30,695.69	$15,426.61

Rehabilitation #3

Third rehabilitation

Rehabilitation Year 2030
Performance Period 10 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Rehabilitation (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$10,796.03
Maintenance	DARWin Calculated	$393.46	$140.18
Total	–	$30,695.69	$10,936.21

Salvage Values

Salvage Year 2040

Cost Information -- Using NPV on a basis of total costs for one direction

Phase	Description	Source	Salvage Value	Net Value
Initial Construction	No salvage value included i ...	User Entered	$0.00	$0.00
Rehabilitation #1	No salvage value included i ...	User Entered	$0.00	$0.00
Rehabilitation #2	No salvage value included i ...	User Entered	$0.00	$0.00
Rehabilitation #3	No salvage value included i ...	User Entered	$0.00	$0.00

Initial Construction Maintenance Costs

Year Maintenance Costs Begin	2005
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Rehabilitation #1 Maintenance Costs

Year Maintenance Costs Begin	2015
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Rehabilitation #2 Maintenance Costs

Year Maintenance Costs Begin	2025
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Rehabilitation #3 Maintenance Costs

Year Maintenance Costs Begin	2035
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $393.46

Initial Construction Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	499	$19,247.88
ACC Binder	T.L.	2	metric ton	$38.57	893	$34,443.57
Aggregate Base-crushed stone	T.L.	3	metric ton	$22.04	3,574	$78,769.51
Geogrid 1	T.L.	4	sq m	$1.25	6,832	$8,540.00
Reduced over excavation	T.L.	5	cu m	$-6.54	299	$-1,953.21

Non Discounted Costs (One Direction)

Traffic Lane	$139,047.74
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $139,047.74

Page 3

Rehabilitation #1 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.84

Non Discounted Costs (One Direction)

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

Rehabilitation #2 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

Rehabilitation #3 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

Initial Construction -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	38
2	ACC Binder	3.66	64
3	Aggregate Base – crushed stone	3.66	254
4	Geogrid 1	4.27	0
5	Reduced over excavation	3.66	51

Initial Construction -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Initial Construction -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Rehabilitation #1 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #1– Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #1– Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #2 – Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #2 -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #2 -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #3 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #3 – Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #3 – Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

1997 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare Computer Software Product
Life Cycle Cost Module

Case 3 Performance period extension (500,000 ESAL'S)

Life Cycle Cost Data Summary

Analysis Period	40 years
Project Length	1.6 km
Discount Rate	3.5 %
Number of Lanes in One Direction	1
Type of Roadway	Undivided

Total Costs Using NPV on a basis of total costs for one direction

Initial Construction Cost	$157,821
Rehabilitation Cost	$15,733
Salvage Value	$0
Total Cost	$173,554

Initial Construction

Initial construction of pavement

Construction Year	2000
Performance Period	20 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$156,816.88	$156,816.88
Maintenance	DARWin Calculated	$1,003.68	$1,003.68
Total	-	$157,820.56	$157,820.56

Rehabilitation #1

First rehabilitation

Rehabilitation Year	2020
Performance Period	20 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$15,228.87
Maintenance	DARWin Calculated	$1,003.68	$504.41
Total	-	$31,305.90	$15,733.28

Salvage Values

Salvage Year 2040

Cost Information -- Using NPV on a basis of total costs for one direction

Phase	Description	Source	Salvage Value	Net Value
Initial Construction	No salvage value included i ...	User Entered	$0.00	$0.00
Rehabilitation #1	No salvage value included i ...	User Entered	$0.00	$0.00

Initial Construction Maintenance Costs

Year Maintenance Costs Begin	2005
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $1,003.68

Rehabilitation #1 Maintenance Costs

Year Maintenance Costs Begin	2025
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $1,003.68

Initial Construction Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	499	$19,247.88
ACC Binder	T.L.	2	metric ton	$38.57	893	$34,443.57
Aggregate Base-crushed stone	T.L.	3	metric ton	$22.04	4,292	$94,585.43
Geogrid 1	T.L.	4	sq m	$1.25	6,832	$8,540.00

Non Discounted Costs (One Direction)

Traffic Lane	$156,816.88
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $156,816.88

Rehabilitation #1 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

Initial Construction -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	38
2	ACC Binder	3.66	68
3	Aggregate Base -- crushed stone	3.66	305
4	Geogrid 1	4.27	0

Initial Construction -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Initial Construction -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Rehabilitation #1 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling Thickness 25.4 mm

Rehabilitation #1 -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #1 -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

1997 AASHTO Pavement Design

DARWin Pavement Design and Analysis System

A Proprietary AASHTOWare Computer Software Product
Life Cycle Cost Module

Case 4 - Combination (500,000 ESAL'S)

Life Cycle Cost Data

Summary

Analysis Period	40 years
Project Length	1.6 km
Discount Rate	3.5 %
Number of Lanes in One Direction	1
Type of Roadwav	Undivided

Total Costs – Using NPV on a basis of total costs for one direction

Initial Construction Cost	$146,387
Rehabilitation Cost	$15,176
Salvage Value	$0
Total Cost	$161,563

Initial Construction

Initial construction of pavement

Construction Year	2000
Performance Period	21 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$145,333.18	$145,333.18
Maintenance	DARWin Calculated	$1,053.93	$1,053.93
Total	-	$146,387.11	$146,387.11

Rehabilitation #1

First rehabilitation

Rehabilitation Year	2021
Performance Period	19 years

Cost Information -- Using NPV on a basis of total costs for one direction

Information Type	Source	Costs at Year of Construction (One Direction)	Net Costs
Construction	DARWin Calculated	$30,302.23	$14,713.88
Maintenance	DARWin Calculated	$951.66	$462.10
Total	-	$31,253.89	$15,175.98

Salvage Values

Salvage Year 2040

Cost Information -- Using NPV on a basis of total costs for one direction

Phase	Description	Source	Salvage Value	Net Value
Initial Construction	No salvage value included i ...	User Entered	$0.00	$0.00
Rehabilitation #1	No salvage value included i ...	User Entered	$0.00	$0.00

Initial Construction Maintenance Costs

Year Maintenance Costs Begin	2005
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $1,053.93

Rehabilitation #1 Maintenance Costs

Year Maintenance Costs Begin	2026
Annual Maintenance Costs	$62.50 per lane km
Annual Increase in Maintenance Costs	0 %

Calculated Non Discounted Maintenance Costs (One Direction) $951.66

Initial Construction Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	499	$19,247.88
ACC Binder	T.L.	2	metric ton	$38.57	893	$34,443.57
Aggregate Base-crushed stone	T.L.	3	metric ton	$22.04	3,574	$78,769.51
Geogrid 2	T.L.	4	sq m	$2.17	6,832	$14,825.44
Reduced over excavation	T.L.	5	cu m	$-6.54	299	$-1,953.21

Non Discounted Costs (One Direction)

Traffic Lane	$145,333.18
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $145,333.18

Page 2

Rehabilitation #1 Pay Items

Name	Lane	Layer	Unit	Unit Cost	Quantity	Total Cost
ACC Surface	T.L.	1	metric ton	$38.57	667	$25,731.37
AC milling	T.L.	2	cu m	$30.73	149	$4,570.85

Non Discounted Costs (One Direction)

Traffic Lane	$30,302.23
Inner Shoulder	$0.00
Outer Shoulder	$0.00
Miscellaneous	$0.00

Total Non Discounted Cost (One Direction) $30,302.23

Initial Construction -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	38
2	ACC Binder	3.66	68
3	Aggregate Base -- crushed stone	3.66	254
4	Geogrid 2	4.27	0
5	Reduced over excavation	3.66	51

Initial Construction -- Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Initial Construction -- Outer Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Rehabilitation #1 -- Traffic Lane Dimensions

Layer	Material Description	Width (m)	Thickness (mm)
1	ACC Surface	3.66	50.8
2	AC milling	3.66	25.4

Milling thickness 25.4 mm

Rehabilitation #1– Inner Shoulder Dimensions

Layer	Material Description	Width (m)	Inner Thickness (mm)	Outer Thickness (mm)

Milling Thickness - mm

Rehabilitation #1 Outer Shoulder Dimensions

Page 3

APPENDIX D — GEOSYNTHETIC REINFORCEMENT MATERIAL SPECIFICATIONS FOR PAVED PERMANENT ROADS

D.1 GEOGRID REINFORCEMENT

This is a material specification for purchasing and does not address installation. Edit notes are presented in the right-hand column. Edit notes are to modify specification to match selected design option(s).

The specification contains two options for specifying geosynthetic reinforcement. One option is to specify materials by an approved products list (APL), with equivalence defined with performance requirements. The other option is to specify geosynthetic reinforcement by generic properties.

The first option (approved products list) should be used with base reinforcement applications, as the mechanisms of geosynthetic base reinforcement are not fully understood and performance of geosynthetics are product-specific. Either specifying option can be applicable to subgrade restraint / stabilization applications, depending on the design procedure. The subgrade restraint specification should be compatible with the design procedure.

This specification is a modification of and supercedes the geogrid specification presented in the GMA White Paper I (1999), except the installation survivability properties.

[BLANK]

Standard Specification
for

Geogrid Base Reinforcement OR Subgrade Restraint of Pavement Structures for Highway Applications

Project Edit Discussion

1. SCOPE

1.1 This is a material specification covering geogrids for use as reinforcement of base OR subbase layers of pavement structures. This is a material purchasing specification and design review of use is recommended.

1.2 This is not a construction specification. This specification is based on required geogrid properties defined by pavement design and by geogrid survivability from installation stresses.

Delete Base Reinforcement or Subgrade Restraint from title.
Delete base or subbase, as appropriate

2. REFERENCED DOCUMENTS

Add reference documents, as required

2.1 *ASTM Standards:*[1]

2.2 GRI Standards:[2]

2.3 U.S. Army Corps of Engineers

1. Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428.
2. Available from Geosynthetic Research Institute, Drexel University, Philadelphia, PA.

3. PHYSICAL REQUIREMENTS

3.1 Polymers used in the manufacture of geogrids shall consist of long-chain synthetic polymers, composed of at least 95 percent by weight of polyolefins, polyesters, or polyamides. They shall be formed into a stable network such that the ribs, filaments or yarns retain their dimensional stability relative to each other, including selvages.

3.2 Geogrids used for reinforcement of base or subbase layers shall conform to the physical requirements of Section 7.

3.3 All property values, with the exception of the coefficient of interaction, coefficient of direct shear, and ultraviolet stability, in these specifications represent minimum average roll values (MARV) in the weakest principle direction (i.e., average test results of any roll in a lot sampled for conformance or quality assurance testing shall meet or exceed the minimum values provided herein).

4. CERTIFICATION AND SUBMITTAL

4.1 The contractor shall provide to the Engineer, a certificate stating the name of the manufacturer, product name, style number, chemical composition of the geogrid product and physical properties applicable to this specification.

4.2 The Manufacturer is responsible for establishing and maintaining a quality control program to assure compliance with the requirements of the specification. Documentation describing the quality control program shall be made available upon request.

4.3 The Manufacturer's certificate shall state that the furnished geogrid meets MARV requirements of the specification as evaluated under the Manufacturer's quality control program. The certificate shall be attested to by a person having legal authority to bind the Manufacturer.

4.4 Either mislabeling or misrepresentation of materials shall be reason to reject those geogrids.

* *

Insert the following for **base reinforcement** applications. Renumber subsequent tables.

* *

Project Edit Discussion

It is recommended that the contracting agency develop a database of projects, and respective material properties, for future use in assessing long-term reinforcement benefits, key reinforcement properties, etc. The following submittal requirements, by application, should used if the agency is developing (or may develop), or is contributing (or may contribute) to the development of (by others), a data base for future evaluation.

4.5 The contractor shall provide to the Engineer, a submittal of the material values for the properties listed in Table 1, for information purposes.

Project Edit Discussion

Table 1. Property Submittal Requirements

Property	Test Method	Units	Value[1]	
Reinforcement Properties[3]			MD[2]	XD[2]
2% & 5 % secant moduli	ASTM D4595[4]	kN/m		
Coef of Pullout Interact.	GRI GG5	–[5]		
Coef of Direct Shear	ASTM D5321	degrees		
Aperture Size	Direct measure	mm		
Percent Open Area	COE CW-02215	%		
Survivability Index Values				
Ult Tensile Strength	ASTM D4595[4]	kN/m		
Junction Strength	GRI GG2	%		
Ultraviolet Stability	ASTM D4355	%		

Notes:
1 Values, except Ultraviolet Stability, Aperture Size, and Coefs are MARVs.
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 The stiffness properties of flexural rigidity and aperture stability are currently being evaluated by the geosynthetic industry, in regards to this application.
4 Modified test method for geogrids.
5 Dimensionless.

See Chapter 10 for additional discussion of stiffness properties.

4.6 The contractor shall provide approximately ___ kg of base (and subbase if applicable) for the agency to test.

The approximate amounts of base (and subbase) required by test are: gradation 8.0 kg for 38 mm max size, 60.0 kg for 75 mm max size; proctor (152 mm diameter) 45 kg; lab CBR 29 kg; moisture 5 kg; direct shear 50 kg*; pullout 1250 kg.*
*Dependent upon box size of test apparatus.

4.7 The contractor shall provide access to the agency for retrieval of asphalt concrete cores. Contractor shall patch core holes.

Cores are required for Marshall stability or elastic modulus, thickness, and in-place bulk density testing. Approximately ____ cores are required.

* *

Insert the following for **subgrade restraint** applications. Renumber subsequent tables.

* *

4.5 The contractor shall provide to the Engineer, a submittal of the material values for the properties listed in Table 1, for information purposes.

Table 1. Property Submittal Requirements

Property	Test Method	Units	Value[1]	
Reinforcement Properties			MD[2]	XD[2]
2% & 5 % secant moduli	ASTM D4595[3]	kN/m		
Aperture Size	Direct measure	mm		
Percent Open Area	COE CW-02215	%		
Survivability Index Values				
Ult Tensile Strength	ASTM D4595[3]	kN/m		
Junction Strength	GRI GG2	%		
Ultraviolet Stability	ASTM D4355	%		

Notes
1 Values, except Ultraviolet Stability and Coefs are MARVs.
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Modified test method for geogrids.

4.6 The contractor shall provide approximately ___ of base (or subbase if applicable) for the agency to test.

Project Edit Discussion

The approximate amounts of base (and subbase) required by test are: gradation 8.0 kg for 38 mm max size, 60.0 kg for 75 mm max size; proctor (152 mm diameter) 29 kg; lab CBR 29 kg; and moisture 5 kg.

5. SAMPLING, TESTING, AND ACCEPTANCE

5.1 Geogrids shall be subject to sampling and testing to verify conformance with this specification. Sampling for testing shall be in accordance with ASTM D 4354. Acceptance shall be based on testing of either conformance samples obtained using Procedure A of ASTM D 4354, or based on manufacturer's certifications and testing of quality assurance samples obtained using Procedure B of ASTM D 4354. A lot size for conformance or quality assurance sampling shall be considered to be the shipment quantity of the given product or a truckload of the given product, whichever is smaller.

5.2 Testing shall be performed in accordance with the methods referenced in this specification for the indicated application. The number of specimens to test per sample is specified by each test method. Geogrid product acceptance shall be based on ASTM D 4759. Product acceptance is determined by comparing the average test results of all specimens within a given sample to the specification MARV. Refer to ASTM D 4759 for more detail regarding geogrid acceptance procedures.

Project Edit Discussion

6. SHIPMENT AND STORAGE

6.1 Geogrids labeling, shipment, and storage shall follow ASTM D 4873. Product labels shall clearly show the manufacturer or supplier name, style name, and roll number. Each shipping document shall include a notation certifying that the material is in accordance with the manufacturer's certificate.

6.2 During storage, geogrid rolls shall be elevated off the ground and adequately covered to protect them from the following: site construction damage, precipitation, extended ultraviolet radiation including sunlight, chemicals that are strong acids or strong bases, flames including welding sparks, temperatures in excess of 71°C (160°F), and any other environmental condition that may damage the physical property values of the geogrid.

7. GEOGRID PROPERTY REQUIREMENTS FOR BASE REINFORCEMENT or SUBGRADE RESTRAINT

Delete BASE REINFORCEMENT or SUBGRADE RESTRAINT, as applicable.

****

Two approaches to specification may be used. An approved products list should be used for designs based upon product-specific data. Generic material specification should be used for designs based upon generic properties. Approved products list approach is presented first. Generic approach follows. Delete section which is not applicable.

****

Delete editorial note.

7.1 The geogrid reinforcements approved for use on this project are listed in Table 1.

7.2 Equivalent Products

7.2.1 Products submitted as equivalent for approval to use shall have documented equivalent, or better, performance in

This is the approved products list approach.

base reinforcement or subgrade restraint in laboratory tests, full-scale field tests, and completed project experience for the project conditions (base course material and thickness, failure criterion, subgrade strength, etc).

7.2.2 Products submitted as equivalent shall have a documented TBR value equal or greater than ___, BCR value equal or greater than ___, or LCR value equal or greater than ___, for the project conditions: base course thickness = ___, subbase thickness = ___, asphalt thickness = ___, failure criterion = ___ mm rut depth, and subgrade strength = ___ CBR.

7.2.3 Products submitted as equivalent for approval to use shall meet, or exceed, the property values listed in Table 2.

Table 1. Approved Geogrid Reinforcement Products

Manufacturer or Distributor	Specific Product Name

****

Equivalent material description (Table 2) may not be desired, or required. Particularly if more than on geogrid is listed on the approved product list, or if a single geogrid is bid against a thicker unreinforced pavement structure option.

****

Table 2. Property Requirements for Equivalent Geogrid Reinforcement Products

Property	Test Method	Units	Required Value[1] MD[2]	XD[2]
Reinforcement Properties				
Survivability Index Values				

Notes
1 Values, except ____ and ____, are MARVs.
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Modified test method for geogrids.

Project Edit Discussion

One or both statements on equivalency may be used for base reinforcement. All three may be used for subgrade restraint.

Edit as appropriate.

Delete 7.2.3 for base reinforcement applications.

Insert approved product(s) that were employed in the design. Note that survivability properties are not listed for approved products, predicated upon assumption that use of approved product is based upon demonstrated performance - also demonstrating survivability.

Delete editorial note.

Insert required reinforcement properties. Values may be based upon the approved products' properties.

Delete Table 2 for base reinforcement applications.

Modify note 1 as appropriate for specified reinforcement properties.

7. GEOGRID PROPERTY REQUIREMENTS FOR SUBGRADE RESTRAINT

7.1 The reinforcement shall meet the requirements of Table 1.

7.1.1 All numeric values in Table 1 represent MARVs with the exception of the ultraviolet light stability, _________, and ______. All numeric values are for the weaker principal direction, unless noted otherwise.

7.1.2 Index, survivability property values in Table 1 represent default values which provide sufficient geogrid survivability under most construction conditions. The geogrid properties required for survivability are dependent upon geogrid elongation.

7.1.3 The geogrid is assumed to be placed with the machine direction (MD - roll length) parallel with the centerline of the roadway alignment. If the geogrid is placed with the machine direction transverse to the centerline of the roadway alignment, the machine (MD) and cross machine direction (XD) tensile strength requirements listed in Table 1 shall be reversed.

Table 1. Geogrid Strength Property Requirements for Subgrade Restraint of Pavements

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
Survivability Index Values				

Notes
1 Values, except Ultraviolet Stability, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Modified test method.

Project Edit Discussion

Section and table numbering as shown if APL option is not used, extend numbering if both options are used. This option is not applicable to base reinforcement applications.

See GMA White Paper I for survivability properties.

Delete 7.1.3 if MD and XD reinforcement properties are not specified.

Insert required reinforcement properties. Properties should be based upon design requirements, agency experience, product manufacturer's recommendations, etc. See GMA WP I for discussion on survivability properties.

D.2 GEOTEXTILE REINFORCEMENT

This is a material specification for purchasing and does not address installation. The specification is in a format similar to the AASHTO M288 specification. However, edit notes are presented in the right-hand column. Edit notes are to modify specification to match selected design option(s).

The specification contains two options for specifying geosynthetic reinforcement. One option is to specify materials by an approved products list (APL), with equivalence defined with performance requirements. The other option is to specify geosynthetic reinforcement by generic properties.

The first option (approved products list) should be used with base reinforcement applications, as the mechanisms of geosynthetic base reinforcement are not fully understood and performance of geosynthetics are product-specific. Either specifying option can be applicable to subgrade restraint / stabilization applications, depending on the design procedure. The subgrade restraint specification should be compatible with the design procedure.

This specification is a modification of and supercedes the geotextile specification presented in the GMA White Paper I (1999), except the installation survivability properties.

.

Standard Specification
for

Geotextile Subgrade Restraint OR Base Reinforcement of Pavement Structures for Highway Applications

Project Edit Discussion

1. SCOPE

1.1 This is a material specification covering geotextiles for use as subgrade restraint or base reinforcement of pavement structures. This is a material purchasing specification and design review of use is recommended.

1.2 This is not a construction specification. This specification is based on required geotextile properties defined by pavement design and by geotextile survivability from installation stresses.

Delete Subgrade Restraint or Base Reinforcement from title. Delete subgrade restraint or base reinforcement, as appropriate.

2. REFERENCED DOCUMENTS

2.1 *ASTM Standards*[1]

D 3786 Test Method for Hydraulic Bursting of Knitted Goods and Nonwoven Fabrics — Diaphragm Bursting Strength Tester Method
D 4354 Practice for Sampling of Geosynthetics for Testing
D 4355 Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus)
D 4533 Test Method for Trapezoid Tearing Strength of Geotextiles
D 4595 Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method
D 4632 Test Method for Grab Breaking Load and Elongation of Geotextiles
D 4751 Test Method for Determining Apparent Opening Size of a Geotextile
D 4759 Practice for Determining the Specification Conformance of Geosynthetics
D 4833 Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products

Add and delete reference documents, as required.

[1] Available from ASTM, 1916 Race Street, Philadelphia, PA 19103-1187.

D 4873 Guide for Identification, Storage, and Handling of Geotextiles
D 4491 Test Methods for Water Permeability of Geotextiles by Permittivity
D 5321 Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method

2.2 GRI Standards:[2]
GT6 Test Method for Geotextile Pullout

3. PHYSICAL REQUIREMENTS

3.1 Fibers used in the manufacture of geotextiles, and the threads used in joining geotextiles by sewing, shall consist of long-chain synthetic polymers, composed of at least 95 percent by weight of polyolefins or polyesters. They shall be formed into a stable network such that the filaments or yarns retain their dimensional stability relative to each other, including selvages.

3.2 Geotextiles used for reinforcement of base or subbase layers shall conform to the physical requirements of Section 7.

3.3 All property values, with the exception of apparent opening size (AOS), in these specifications represent minimum average roll values (MARV) in the weakest principle direction (i.e., average test results of any roll in a lot sampled for conformance or quality assurance testing shall meet or exceed the minimum values provided herein). Values for AOS represent maximum average roll values.

4. CERTIFICATION AND SUBMITTAL

4.1 The contractor shall provide to the Engineer, a certificate stating the name of the manufacturer, product name, style number, chemical composition of the filaments or yarns and other pertinent information to fully describe the geotextile.

4.2 The Manufacturer is responsible for establishing and maintaining a quality control program to assure compliance with the requirements of the specification. Documentation describing the quality control program shall be made available upon request.

4.3 The Manufacturer's certificate shall state that the furnished geotextile meets MARV requirements of the specification as evaluated under the Manufacturer's quality control program. The certificate shall be attested to by a person having legal authority to bind the Manufacturer.

Project Edit Discussion

Delete or add references to material properties

4.4 Either mislabeling or misrepresentation of materials shall be reason to reject those geotextiles.

* *

Insert the following for **base reinforcement** applications. Renumber subsequent tables.

* *

4.5 The contractor shall provide to the Engineer, a submittal of the material values for the properties listed in Table 1, for information purposes.

Table 1. Geotextile Strength Property Requirements for Base Reinforcement of Pavements

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
2% & 5 % Secant Moduli				
Coef of Pullout Interact.				
Coef of Direct Shear				
Permittivity	ASTM D4491	sec^{-1}	0.05 [3]	
Apparent Opening Size	ASTM D4751	mm	0.60 max. avg	
Survivability Index Values			Elong < 50%[4]	Elong ≥ 50%[4]
Grab Strength	ASTM D4632	N	1400	900
Sewn Seam Strength[5]	ASTM D4632	N	1260	810
Tear Strength	ASTM D4533	N	500	350
Puncture Strength	ASTM D4833	N	500	350
Burst Strength	ASTM D3786	kPa	3500	1700
Ultraviolet Stability	ASTM D4355	%	>50%, 500 hrs	

Notes

1. Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2. MD - machine, or roll, direction; XD - cross machine, or roll, direction
3. Default value. Permittivity of the geotextile should be greater than that of the soil ($\psi_g > \psi_s$). The Engineer may also require the permeability of the geotextile to be greater than that of the soil ($k_g > k_s$).
4. As measured in accordance with ASTM D 4632.
5. When sewn seams are required.

4.6 The contractor shall provide approximately ___ kg of base (and subbase if applicable) for the agency to test.

4.7 The contractor shall provide access to the agency for retrieval of asphalt concrete cores. Contractor shall patch core holes.

Project Edit Discussion

It is recommended that the contracting agency develop a database of projects, and respective material properties, for future use in assessing long-term reinforcement benefits, key reinforcement properties, etc. The following submittal requirements, by application, should used if the agency is developing (or may develop), or is contributing (or may contribute) to the development of (by others), a data base for future evaluation.

The approximate amounts of base (and subbase) required by test are: gradation 8.0 kg for 38 mm max size, 60.0 kg for 75 mm max size; proctor (152 mm diameter) 45 kg; lab CBR 29 kg; moisture 5 kg; direct shear 50 kg*; pullout 1250 kg*

*Dependent upon box size of test apparatus.

Cores are required for Marshall stability or elastic modulus, thickness, and in-place bulk density testing. Approximately cores are required.

* *

Insert the following for **subgrade restraint** applications. Renumber subsequent tables.

* *

4.5 The contractor shall provide to the Engineer, a submittal of the material values for the properties listed in Table 1, for information purposes.

Table 1. Geotextile Strength Property Requirements for Subgrade Restraint of Pavements

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
2% & 5 % Secant Moduli				
Permittivity	ASTM D4491	sec^{-1}	0.05 [3]	
Apparent Opening Size	ASTM D4751	mm	0.60 max. avg	
Survivability Index Values			Elong < 50%[4]	Elong ≥ 50%[4]
Grab Strength	ASTM D4632	N	1400	900
Sewn Seam Strength[5]	ASTM D4632	N	1260	810
Tear Strength	ASTM D4533	N	500	350
Puncture Strength	ASTM D4833	N	500	350
Burst Strength	ASTM D3786	kPa	3500	1700
Ultraviolet Stability	ASTM D 4355	%	>50%, 500 hrs	

Notes
1 Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Default value. Permittivity of the geotextile should be greater than that of the soil ($\psi_g > \psi_s$). The Engineer may also require the permeability of the geotextile to be greater than that of the soil ($k_g > k_s$).
4 As measured in accordance with ASTM D 4632.
5 When sewn seams are required.

4.6 The contractor shall provide approximately __ kg of base (or subbase if applicable) for the agency to test.

* *

Project Edit Discussion

The approximate amounts of base (and subbase) required by test are: gradation 8.0 kg for 38 mm max size, 60.0 kg for 75 mm max size; proctor (152 mm diameter) 29 kg; lab CBR 29 kg; and moisture 5 kg

5. SAMPLING, TESTING, AND ACCEPTANCE

5.1 Geotextiles shall be subject to sampling and testing to verify conformance with this specification. Sampling for testing shall be in accordance with ASTM D 4354. Acceptance shall be based on testing of either conformance samples obtained using Procedure A of ASTM D 4354, or based on manufacturer's certifications and testing of quality assurance samples obtained using Procedure B of ASTM D 4354. A lot size for conformance or quality assurance sampling shall be considered to be the shipment quantity of the given product or a truckload of the given product, whichever is smaller.

5.2 Testing shall be performed in accordance with the methods referenced in this specification for the indicated application. The number of specimens to test per sample is specified by each test method. Geotextile product acceptance shall be based on ASTM D 4759. Product acceptance is determined by comparing the average test results of all specimens within a given sample to the specification MARV. Refer to ASTM D 4759 for more detail regarding geotextile acceptance procedures.

6. SHIPMENT AND STORAGE

6.1 Geotextiles labeling, shipment, and storage shall follow ASTM D 4873. Product labels shall clearly show the manufacturer or supplier name, style name, and roll number. Each shipping document shall include a notation certifying that the material is in accordance with the manufacturer's certificate.

6.2 Each geotextile roll shall be wrapped with a material that will protect the geotextile from damage due to shipment, water, sunlight, and contaminants. The protective wrapping shall be maintained during periods of shipment an storage.

6.3 During storage, geotextile rolls shall be elevated off the ground and adequately covered to protect them from the following: site construction damage, precipitation, extended ultraviolet radiation including sunlight, chemicals that are strong acids or strong bases, flames including welding sparks, temperatures in excess of 71°C (160°F), and any other environmental condition that may damage the physical property values of the geotextile.

Project Edit Discussion

It is recommended that the contracting agency develop a database of projects, and respective material properties, for future use in assessing long-term reinforcement benefits, key reinforcement properties, etc. The following submittal requirements, by application, should used if the agency is developing (or may develop), or is contributing (or may contribute) to the development of (by others), a data base for future evaluation.

7. GEOTEXTILE PROPERTY REQUIREMENTS FOR SUBGRADE RESTRAINT

****

Two approaches to specification may be used. Generic material specification should be used for designs based upon generic properties. An approved products list should be used for designs based upon product-specific data. Generic approach is presented first, delete if not applicable. Approved products list approach follows.

****

7.1 The geotextile reinforcement shall meet the requirements of Table 1.

7.1.1 All numeric values in Table 1 represent MARVs with the exception of the ultraviolet light stability, _________, and ______. All numeric values are for the weaker principal direction, unless noted otherwise.

7.1.2 The index, survivability property values in Table 1 represent default values which provide sufficient geotextile survivability under most construction conditions. The geotextile properties required for survivability are dependent upon geotextile elongation.

7.1.3 The geotextile is assumed to be placed with the machine direction (MD - roll length) parallel with the centerline of the roadway alignment. If the geotextile is placed with the machine direction transverse to the centerline of the roadway alignment, the machine (MD) and cross machine direction (XD) tensile strength requirements listed in Table 1 shall be reversed.

Project Edit Discussion

Generic specification approach only applicable to Subgrade Restraint

Delete editorial note.

Insert additional specified properties, dependent upon design procedure.

The Design Engineer may also specify properties different from those listed in Table 1 based on engineering design experience.

Delete 7.1.3 if MD and XD reinforcement properties are not specified.

Table 1. Geotextile Strength Property Requirements for Subgrade Restraint of Pavements

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
2% & 5 % Secant Moduli	ASTM D4595	kN/m		
Coef of Pullout Interact.	GRI GT6	--[4]		
Coef of Direct Shear	ASTM D5321	degrees		
Permittivity	ASTM D4491	sec^{-1}	0.05 [3]	
Apparent Opening Size	ASTM D4751	mm	0.60 max. avg	
Survivability Index Values			Elong < 50%[4]	Elong ≥ 50%[4]
Grab Strength	ASTM D4632	N	1400	900
Sewn Seam Strength[5]	ASTM D4632	N	1260	810
Tear Strength	ASTM D4533	N	500	350
Puncture Strength	ASTM D4833	N	500	350
Burst Strength	ASTM D3786	kPa	3500	1700
Ultraviolet Stability	ASTM D 4355	%	>50%, 500 hrs	

Notes
1 Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Default value. Permittivity of the geotextile should be greater than that of the soil ($\psi_g > \psi_s$). The Engineer may also require the permeability of the geotextile to be greater than that of the soil ($k_g > k_s$).
4 As measured in accordance with ASTM D 4632.
5 When sewn seams are required.

7. GEOTEXTILE PROPERTY REQUIREMENTS FOR SUBGRADE RESTRAINT or BASE REINFORCEMENT

****

Two approaches to specification may be used. Generic material specification should be used for designs based upon generic properties. An approved products list should be used for designs based upon product-specific data. Approved products list approach follows.

****

7.1 The geotextile reinforcements approved for use on this project are listed in Table 1.

7.2 Equivalent Products

7.2.1 Products submitted as equivalent for approval to use shall have documented equivalent, or better, performance in base reinforcement or subgrade restraint in laboratory tests, full-scale field tests, and completed project experience for the

Project Edit Discussion

Insert required reinforcement properties. Those listed are for base reinforcement from discussion in Section 7 of the white paper. Delete Coefficients of Pullout and of Direct Shear for subgrade restraint specification. Additional properties may be added, based upon agency experience, product manufacturer's recommendations, etc.

Survivability properties listed are for subgrade restraint, from Section 7 discussion and after AASHTO M288 specification. Add Ultimate Tensile Strength and delete Grab, Seam, Puncture, and Burst strengths for base reinforcement applications.

Modify note 1 as appropriate for specified reinforcement properties.

Delete Subgrade Restraint or Base Reinforcement, as appropriate.

Delete editorial note.

Section and table numbering as shown if generic option is not used, extend numbering if both options are used.

This is the approved products list approach.

project conditions (base

course material and thickness, failure criterion, subgrade strength, etc).

7.2.2 Products submitted as equivalent shall have a documented TBR value equal or greater than ___, BCR value equal or greater than ___, or LCR value equal or greater than ___, for the project conditions: base course thickness = ___, subbase thickness = ___, asphalt thickness = ___, failure criterion = ___ mm rut depth, and subgrade strength = ___ CBR.

7.2.3 Products submitted as equivalent for approval to use shall meet, or exceed, the property values listed in Table 2.

****

Equivalent material description (Table 2) may not be desired, or required. Particularly if more than on geotextile is listed on the approved product list, or if a single geotextile is bid against a thicker unreinforced pavement structure option.

****

Table 1. Approved Geotextile Reinforcement Products

Manufacturer or Distributor	Specific Product Name

Table 2. Property Requirements for Equivalent Geotextile Reinforcement Products

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
Survivability Index Values				

Notes
1 Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Permittivity of the geotextile should be greater than that of the soil ($\psi_g > \psi_s$). The Engineer may also require the permeability of the geotextile to be greater than that of the soil ($k_g > k_s$).

Project Edit Discussion

Note that survivability properties are not listed for approved products, predicated upon assumption that use of approved product is based upon demonstrated performance - also demonstrating survivability.

Delete 7.2.3 for base reinforcement applications

Insert approved product(s) that were employed in the design

Insert required reinforcement properties. Values may be based upon the approved products' properties.

Delete Table 2 for base reinforcement applications.

Modify note 1 as appropriate for specified reinforcement properties.

D.3 GEOGRID-GEOTEXTILE COMPOSITE REINFORCEMENT

This is a material specification for purchasing and does not address installation. Edit notes are presented in the right-hand column. Edit notes are to modify specification to match selected design option(s).

The specification contains two options for specifying geosynthetic reinforcement. One option is to specify materials by an approved products list (APL), with equivalence defined with performance requirements. The other option is to specify geosynthetic reinforcement by generic properties.

The first option (approved products list) should be used with base reinforcement applications, as the mechanisms of geosynthetic base reinforcement are not fully understood and performance of geosynthetics are product-specific. Either specifying option can be applicable to subgrade restraint / stabilization applications, depending on the design procedure. The subgrade restraint specification should be compatible with the design procedure.

The specification is applicable to both a bonded GG-GT composite and to an unbonded GG-GT composite. Refer to GMA White Paper I (1999) for geogrid and geotextile survivability properties.

Standard Specification
for

Geogrid-Geotextile Composite Base Reinforcement OR Subgrade Restraint of Pavement Structures for Highway Applications

Project Edit Discussion

1. SCOPE

1.1 This is a material specification covering geogrid-geotextile composite for use as reinforcement of base or subbase layers of pavement structures. This is a material purchasing specification and design review of use is recommended.

1.2 This is not a construction specification. This specification is based on required geogrid-geotextile composite properties defined by pavement design and by composite survivability from installation stresses.

Delete Subgrade Restraint or Base Reinforcement from title. Delete subgrade restraint or base reinforcement, as appropriate.

2. REFERENCED DOCUMENTS

2.1 *ASTM Standards*[1]*:*

D 4355 Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus)

Add reference documents, as required.

2.2 GRI Standards[2]:

3. PHYSICAL REQUIREMENTS

3.1 Polymers used in the manufacture of geogrid-geotextile composites, and the mechanical fasteners or threads used to join adjacent rolls, shall consist of long-chain synthetic polymers, composed of at least 95 percent by weight of polyolefins, polyesters, or polyamides. They shall be formed into a stable network such that the ribs, filaments or yarns retain their dimensional stability relative to each other, including selvages.

1. Available from ASTM, 1916 Race Street, Philadelphia, PA 19103-1187.
2. Available from Geosynthetic Research Institute, Drexel University, Philadelphia, PA.

3.2 Geogrid-geotextile composites used for reinforcement of base or subbase layers shall conform to the physical requirements of Section 7.

3.3 All property values, with the exception of the coefficient of interaction, coefficient of direct shear, and ultraviolet stability, in these specifications represent minimum average roll values (MARV) in the weakest principle direction (i.e., average test results of any roll in a lot sampled for conformance or quality assurance testing shall meet or exceed the minimum values provided herein).

Project Edit Discussion

3. CERTIFICATION AND SUBMITTAL

4.1 The contractor shall provide to the Engineer, a certificate stating the name of the manufacturer, product name, style number, chemical composition of the geogrid-geotextile product and physical properties applicable to this specification.

4.2 The Manufacturer is responsible for establishing and maintaining a quality control program to assure compliance with the requirements of the specification. Documentation describing the quality control program shall be made available upon request.

4.3 The Manufacturer's certificate shall state that the furnished composite meets MARV requirements of the specification as evaluated under the Manufacturer's quality control program. The certificate shall be attested to by a person having legal authority to bind the Manufacturer.

4.4 Either mislabeling or misrepresentation of materials shall be reason to reject those composite products.

* *

Insert the following for **base reinforcement** applications. Renumber subsequent tables.

* *

4.5 The contractor shall provide to the Engineer, a submittal of the material values for the properties listed in Table 1, for information purposes.

It is recommended that the contracting agency develop a database of projects, and respective material properties, for future use in assessing long-term reinforcement benefits, key reinforcement properties, etc. The following submittal requirements, by application, should used if the agency is developing (or may develop), or is contributing (or may contribute) to the development of (by others), a data base for future evaluation.

Table 1. Geogrid-Geotextile Composite Property Submittal Requirements for Base Reinforcement of Flexible Pavements

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties[3]			MD[2]	XD[2]
2% & 5 % Secant Moduli	ASTM D4595[4]	kN/m		
Flexural Rigidity	ASTM D5732[4]	mg/cm^2		
Coef of Pullout Interact.	GRI GG5	–[5]		
Coef of Direct Shear	ASTM D5321	degrees		
Permittivity	ASTM D4491	mm		
Apparent Opening Size	ASTM D4751	sec^{-1}		
Survivability Index Values			Elong < 50%	Elong ≥ 50%
Ult Tensile Strength	ASTM D4595[4]	N		
Ultraviolet Stability	ASTM D 4355	%	>__%, ___ hrs	

Notes
1 Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 The stiffness properties of flexural rigidity and aperture stability are currently being evaluated by the geosynthetic industry, in regards to this application.
4 Modified test method.
5 Dimensionless.

4.6 The contractor shall provide approximately ___ kg of base (and subbase if applicable) for the agency to test.

4.7 The contractor shall provide access to the agency for retrieval of asphalt concrete cores. Contractor shall patch core holes.

* *

Insert the following for **subgrade restraint** applications. Renumber subsequent tables.

* *

4.5 The contractor shall provide to the Engineer, a submittal of the material values for the properties listed in Table 1, for information purposes.

Project Edit Discussion

See Chapter 10 for additional discussion of stiffness properties.

The approximate amounts of base (and subbase) required by test are: gradation 8.0 kg for 38 mm max size, 60.0 kg for 75 mm max size; proctor (152 mm diameter) 45 kg; lab CBR 29 kg; moisture 5 kg; direct shear 50 kg*; pullout 1250 kg*
*Dependent upon box size of test apparatus.

Cores are required for Marshall stability or elastic modulus, thickness, and in-place bulk density testing. Approximately ____ cores are required.

Table 1. Geogrid-Geotextile Composite Property Submittal Requirements for Subgrade Restraint Reinforcement

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
2% & 5 % Secant Moduli Permittivity Apparent Opening Size	ASTM D4595[3] ASTM D4491 ASTM D4751	kN/m mm sec^{-1}		
Survivability Index Values			Elong < 50%	Elong ≥ 50%
Ult Tensile Strength Ultraviolet Stability	ASTM D4595[3] ASTM D 4355	N %	>__%, ___ hrs	

Notes
1 Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction
3 Modified test method.
4 Dimensionless.

4.6 The contractor shall provide approximately ___ of base (or subbase if applicable) for the agency to test.

* *

5. SAMPLING, TESTING, AND ACCEPTANCE

5.1 Composites shall be subject to sampling and testing to verify conformance with this specification. Sampling for testing shall be in accordance with ASTM D 4354. Acceptance shall be based on testing of either conformance samples obtained using Procedure A of ASTM D 4354, or based on manufacturer's certifications and testing of quality assurance samples obtained using Procedure B of ASTM D 4354. A lot size for conformance or quality assurance sampling shall be considered to be the shipment quantity of the given product or a truckload of the given product, whichever is smaller.

5.2 Testing shall be performed in accordance with the methods referenced in this specification for the indicated application. The number of specimens to test per sample is specified by each test method. Geogrid-geotextile composite product acceptance shall be based on ASTM D 4759. Product acceptance is determined by comparing the average test results of all specimens within a given sample to the specification MARV. Refer to ASTM D 4759 for more detail regarding acceptance procedures.

6. SHIPMENT AND STORAGE

Project Edit Discussion

The approximate amounts of base (and subbase) required by test are: gradation 8.0 kg for 38 mm max size, 60.0 kg for 75 mm max size; proctor (152 mm diameter) 29 kg; lab CBR 29 kg; and moisture 5 kg.

6.1 Composite

labeling, shipment, and storage shall follow ASTM D 4873. Product labels shall clearly show the manufacturer or supplier name, style name, and roll number. Each shipping document shall include a notation certifying that the material is in accordance with the manufacturer's certificate.

6.2 During storage, composite rolls shall be elevated off the ground and adequately covered to protect them from the following: site construction damage, precipitation, extended ultraviolet radiation including sunlight, chemicals that are strong acids or strong bases, flames including welding sparks, temperatures in excess of 71°C (160°F), and any other environmental condition that may damage the physical property values of the composite.

7. GEOGRID-GEOTEXTILE COMPOSITE PROPERTY REQUIREMENTS FOR BASE REINFORCEMENT AND SUBGRADE RESTRAINT

****

Two approaches to specification may be used. An approved products list should be used for designs based upon product-specific data. Generic material specification should be used for designs based upon generic properties. Approved products list approach is presented first. Generic approach follows. Delete section which is not applicable.

****

7.1 The GG-GT composite reinforcements approved for use on this project are listed in Table 1.

7.2 Equivalent Products

7.2.1 Products submitted as equivalent for approval to use shall be (i) a bonded GG-GT composite; or (ii) an unbonded GG-GT composite; or (iii) either bonded or unbonded are acceptable.

7.2.2 Products submitted as equivalent for approval to use shall have documented equivalent, or better, performance in base reinforcement or subgrade restraint in laboratory tests, full-scale field tests, and completed project experience for the project conditions (base course material and thickness, failure criterion, subgrade strength, etc).

Project Edit Discussion

Delete BASE REINFORCEMENT or SUBGRADE RESTRAINT, as applicable.

Delete editorial note.

This is the approved products list approach.

Use either (i), (ii) or (iii) under 7.2.1.

One, two, or all three statements on equivalency may be used.

7.2.3 Products

submitted as equivalent shall have a documented TBR value equal or greater than ___, BCR value equal or greater than ___, or LCR value equal or greater than ___, for the project conditions: base course thickness = ___, subbase thickness = ___, asphalt thickness = ___, failure criterion = ___ mm rut depth, and subgrade strength = ___ CBR.

7.2.4 Products submitted as equivalent for approval to use shall meet, or exceed, the property values listed in Table 2.

****

Equivalent material description (Table 2) may not be desired, or required. Particularly if more than on composite is listed on the approved product list, or if a single composite is bid against a thicker unreinforced pavement structure option.

****

Table 1. Approved Composite Reinforcement Products

Manufacturer or Distributor	Specific Product Name

Table 2. Property Requirements for Equivalent Composite Reinforcement Products

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
Survivability Index Values				
Ultraviolet Stability	ASTM D 4355	%	minimum 50% after 500 hours	

Notes
1 Values, except Ultraviolet Stability, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction

Project Edit Discussion

Delete 7.2.4 for base reinforcement applications.

Delete editorial note.

Insert approved product(s) that were employed in the design.

Note that survivability properties are not listed for approved products, predicated upon assumption that use of approved product is based upon demon-strated performance - also demonstrating survivability. Insert required reinforcement properties such as tensile strength at 2% or 5% strain per ASTM D 4595; coefficient of direct shear; etc.; etc.; which are defined by the approved pro-duct(s). May take from the product manu-facturer's literature.

Insert survivability index properties such as grab strength; tear strength; etc.; which are defined by the approved product(s). May take from the product manufacturer's literature.

Modify note 1 as appropriate for speci-fied reinforcement properties.

Delete Table 2 for base reinforcement applications.

7. GEOGRID-GEOTEXTILE COMPOSITE PROPERTY REQUIREMENTS FOR SUBGRADE RESTRAINT

7.1 The reinforcement shall be (i) a bonded GG-GT composite; or (ii) an unbonded GG-GT composite; or (iii) either bonded or unbonded are acceptable and shall meet the requirements of Table 1.

7.1.1 All numeric values in Table 1 represent MARVs with the exception of the ultraviolet light stability, _________, and ______. All numeric values are for the weaker principal direction, unless noted otherwise.

7.1.2 The composite is assumed to be placed with the machine direction (MD - roll length) parallel with the centerline of the roadway alignment. If the composite is placed with the machine direction transverse to the centerline of the roadway alignment, the machine (MD) and cross machine direction (XD) tensile strength requirements listed in Table 1 shall be reversed.

Table 1. Composite Strength Property Requirements for Subgrade Restraint of Pavements

Property	Test Method	Units	Required Value[1]	
Reinforcement Properties			MD[2]	XD[2]
Survivability Index Values				
---	ASTM ---	--	--	
---	---	--	--	
Ultraviolet Stability	ASTM D 4355	%	minimum 50% after 500 hours	

Notes
1 Values, except Ultraviolet Stability, Apparent Opening Size, ____ and ____, are MARVs (average value minus two standard deviations).
2 MD - machine, or roll, direction; XD - cross machine, or roll, direction

Project Edit Discussion

Section and table numbering as shown if APL option is not used. This option is not applicable to base reinforcement applications.

Use either (i), (ii) or (iii) under 7.1

Insert additional specified properties, dependent upon design procedure. The Design Engineer may also specify properties different from those listed in Table 1 based on engineering design experience.

Delete 7.1.2 if MD and XD reinforcement properties are not specified.

Insert required reinforcement properties such as tensile strength at 2% or 5% strain per ASTM D 4595; coefficient of direct shear; etc.; etc.
Insert required survivability index values based upon experience.

APPENDIX E — DOCUMENTATION OF BENEFIT BY TEST SECTION EVALUATION

E.1 INTRODUCTION

The *Recommended Practice* described in Section 8 along with the draft specifications presented in Appendix D presents an option where the designer is required to define benefit, as designated by TBR or BCR, for specific project conditions, typical agency-specific conditions and/or specific geosynthetic products. Requiring a definition of benefit may arise through one of the following reasons:

1. Project or typical agency conditions — including AC thickness, base aggregate thickness, type and quality, subbase thickness, type and quality, subgrade CBR strength, load magnitude and/or number of load applications — significantly differ from those conditions documented in this report, which have been used to demonstrate benefit.
2. The geosynthetic manufacturing process significantly differs from those conditions documented in this report, which have been used to demonstrate benefit.
3. Equivalent geosynthetic products listed in a project specification require the documentation of equivalent or better TBR or BCR values.

Documentation of benefit should be by the empirical means of constructing test sections with and without geosynthetic for the design, or similar, conditions of interest. In this manner, documentation of benefit is obtained by a performance test mimicking the design conditions appropriate for the application. Documentation of benefit by analytical techniques has not progressed to the point where this approach can be recommended at this time. The purpose of this section is to describe the types of test sections that can be constructed to allow for documentation of benefit and the manner in which these test sections should be constructed, loaded, monitored, and reported.

E.2 TYPES OF APPROPRIATE TEST SECTIONS

For purposes of this document, a test section is defined as a single test arrangement for a given set of pavement layer and reinforcement conditions. Generally, two test sections, one containing reinforcement and one without, are needed for any determination of benefit.

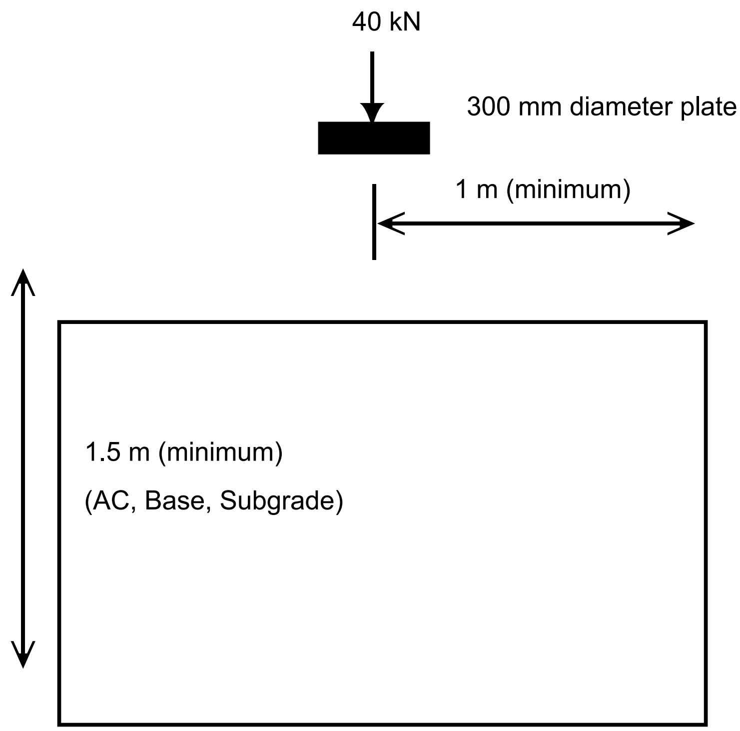


Figure E-1. Minimum box dimensions, plate load and plate dimensions for a test-box pavement test facility.

Test sections may be constructed and loaded in either a test-box facility or a facility allowing for the construction of a test-track. Minimum dimensions for the geometry of a test-box are given in Figure E-1. The box may be square or circular in plan view and should be sufficiently rigid to prevent lateral movement of the box sides during the application of pavement load. A pavement load of 40 kN should be applied to a circular plate having a diameter of 300 mm. The plate should be sufficiently rigid to prevent bending of the plate during the application of pavement load. A waffled rubber pad should be placed between the plate and the asphalt concrete layer to aid in providing a uniform pressure to the pavement and to avoid stress concentrations along the plate edge. The plate load should be applied at a constant frequency usually no greater than about 1 Hz. The duration of the loading-unloading pulse for each cycle should be between 0.1 to 1 second. Load applied to the plate should be measured and recorded for the following load cycle numbers: 1, 2, 4, 8, 16, 32, 50, 100, and doubling cycle numbers thereafter. The mean, standard deviation and coefficient of variation of the applied load as measured over the entire test should be computed and reported. Each cycle of pavement load will be considered to be one ESAL.

Test sections may also be constructed in the form of a test-track where a moving wheel is used to apply pavement load. Test-tracks may be constructed within a long, contained box or by excavation of natural ground and replacement with test section materials of interest. Minimum dimensions of the materials contained in the test-track are shown in Figure E-2. Like the test-box, the minimum depth of a test-track box or the minimum thickness of all materials placed within an excavated pit is 1.5 m. The minimum distance between the centerline of the outermost wheel and the edge of the test-track should be 1 m. The minimum length of a test-track is dependent on the type of load applied and is discussed below.

Load to a test-track can be provided by either a single wheel mounted to a load cart or frame, or by actual truck traffic operating on the test-track. The minimum length of the test-track for each case is 2 m and 8 m, respectively. Applied traffic can either be channeled or have a degree of wander incorporated into the traffic passes.

If a single wheel is used, the wheel should resemble a typical semi-truck tire, be inflated to 560 kPa, and carry a 40 kN load. If load is applied through a system other than that involving the application of load through static dead-weight, load should be measured and recorded for the following traffic passes: 1, 2, 4, 8, 16, 32, 50, 100, and doubling cycle numbers thereafter. If load is periodically measured and recorded, the mean, standard deviation and coefficient of variation of the load as measured over the entire test should be computed and reported. The wheel speed should be no less than about 0.5 m/sec. Each traffic pass of a wheel of this configuration will be counted as one ESAL. If truck traffic is applied, a single truck of a known type should be used. The load from each axle should be determined at the outset of testing such that the number of ESALs for each traffic pass can be computed. Measurements of axle load and the computation of ESALs for the truck should be reported. Additionally, the wheel type(s), axle configuration, and number of wheels per axle should be reported.

A test-box or a test-track can be constructed indoors or outdoors. In either situation, the temperature difference during loading of all test sections used for comparison should not exceed 10° C. Outdoor test facilities should be protected from precipitation to prevent water from seeping into underlying pavement materials. Soil and pavement materials placed within a test section should not be allowed to freeze at any point during construction or loading.

Permanent deformation of the pavement surface should be measured after the following traffic passes, where the traffic passes correspond to ESAL numbers: 1, 2, 4, 8, 16, 32, 50, 100, and doubling thereafter. Permanent deformation is defined as the vertical movement in the pavement load footprint as measured from a fixed datum and measured when the pavement load is removed. For a test-box facility, permanent deformation should be measured in at least two opposite points under the footprint of the load plate. The permanent deformation recorded should be the mean of the measurements taken under the plate footprint.

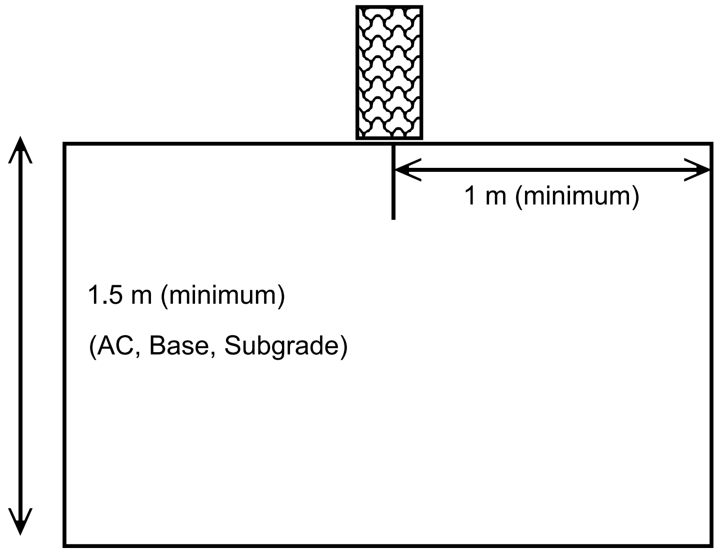


Figure E-2. Minimum dimensions for a test-track pavement test facility.

For a test-track facility, permanent deformation should be measured at 4 locations along the length of the wheel path. These locations should be at the 3, 4, 5 and 6 m points of an 8 m-long section and scaled appropriately for sections of other lengths. If a single wheel load is applied, permanent deformation at each of these 4 locations should be computed by taking a minimum of 3 measurements across the width of the wheel path and recording the mean of these measurements. If truck traffic with single wheel axles is applied, 3 measurements should be taken across the width of each of the two single wheel paths. The 6 measurements taken should be averaged and recorded for each of the 4 measurement locations. If dual wheel axles are used, 3 measurements should be taken across the width of each of the 4 individual wheel paths, with the 12 measurements averaged and recorded for each of the 4 measurement locations. The mean measurement of permanent deformation for each of the 4 measurement locations along the length of the wheel path should be averaged and plotted against the applied ESAL. The standard deviation and coefficient of variation of these 4 mean values should be reported for the permanent deformations corresponding to the end of the test or for a mean permanent deformation of 25 mm, whichever is first.

Pavement traffic passes and load should be applied until the permanent deformation used to define pavement life in the design application being modeled is reached. For test section comparisons involving the computation of TBR, and if TBR increases with increasing traffic passes, test section loading may be stopped prior to reaching the permanent deformation assumed for design. The TBR achieved at the conclusion of the test should then be the TBR used for design purposes. For test section comparisons involving the computation of BCR, and if comparative test sections demonstrate equal performance (i.e., show the same level of permanent deformation), test section loading may be stopped prior to reaching the permanent deformation assumed for design. For either case, load should be applied until at least 12.5 mm of permanent deformation is observed in all test sections.

E.3 SELECTION OF TEST SECTION MATERIALS

Materials (asphalt concrete, base and subbase aggregate, subgrade soil, geosynthetic) selected for use in the construction of test sections should match as closely as possible the type and properties of those anticipated for use in the design situation of interest. Given the difficulty associated with matching material properties and characteristics for situations where test section materials come from geographic locations other than those for the design of interest, allowances are provided for adjusting asphalt concrete and aggregate base and subbase thickness for materials of somewhat different material properties.

For the asphalt concrete, a material should be chosen that represents the same class of quality as that proposed for use in the design situation. In general, hot plant-mix asphalt concrete should be used. An asphalt concrete structural layer coefficient of the material proposed for use in the design and the proposed design thickness should be known and provided. The layer coefficient of the in-place asphalt concrete in the test section should also be known or assumed. Layer coefficient of in-place material should be determined from correlations with Marshall stability (Figure E-3) or elastic (resilient) modulus (Figure E-4). Marshall stability should be determined on in-place test section asphalt concrete cores as per AASHTO test method T-245. Resilient modulus should be determined on in-place test section asphalt concrete cores as per ASTM D4123. The number of test samples from which either Marshall stability or elastic modulus should be determined is given in Section E.5.

The maximum difference between the assumed layer coefficient and the actual coefficient determined through correlations with either Marshall stability or elastic modulus on in-place test section cores should be ± 0.02, where the in-place value represents the mean of all values obtained for samples from the test section. In construction of the test section, the thickness of the asphalt concrete layer should be adjusted from that in the design condition such that the product of layer coefficient and thickness is identical between the test section and design.

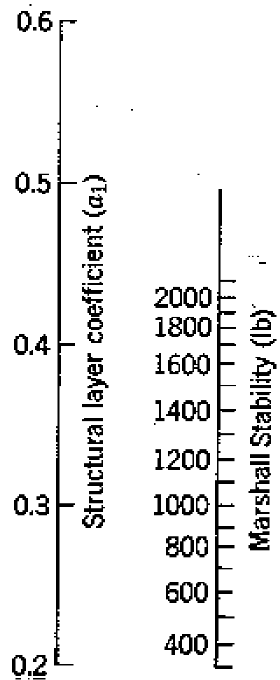


Figure E-3. Correlation between asphalt concrete structural layer coefficient, a_1, and Marshall stability (after Van Til et al., 1972).

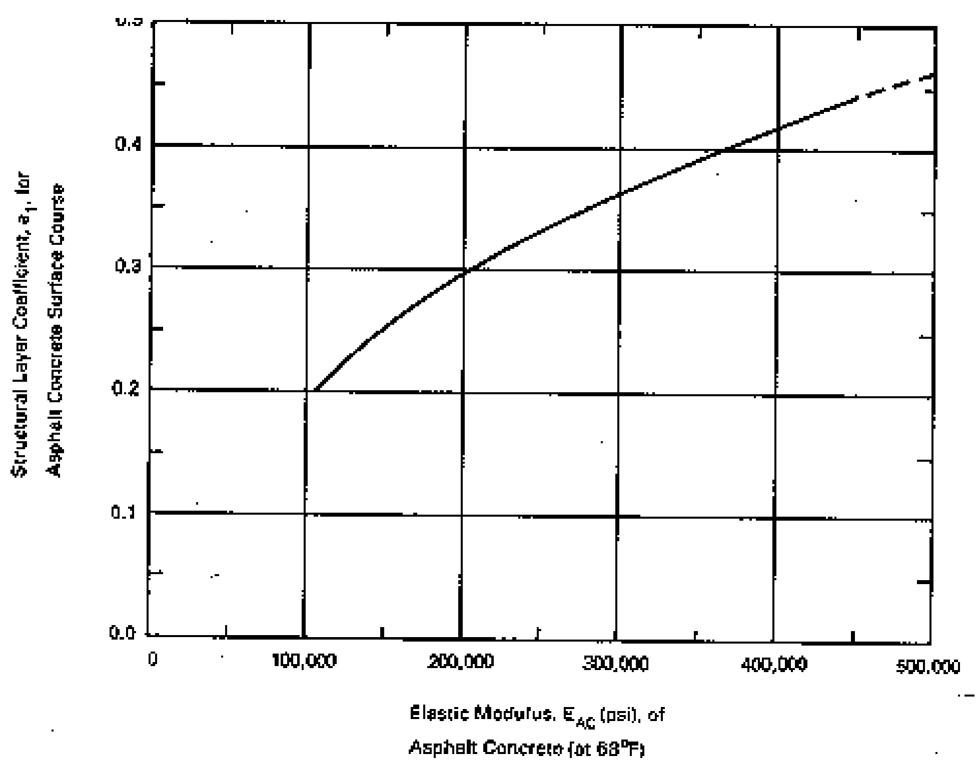


Figure E-4. Correlation between asphalt concrete structural layer coefficient, a_1, and elastic (resilient) modulus (AASHTO, 1993).

For the base aggregate, test section material should be chosen to match the gradation, plasticity indices, fractured faces, and particle structural integrity as closely as possible to that used in the design situation. A base aggregate structural layer coefficient of the material proposed for use in the design and the design thickness should be known and provided. The layer coefficient of the in-place base aggregate in the test section should be determined from correlations with CBR, R-value, Texas-triaxial, and/or resilient modulus (Figure E-5). An appropriate value for correlation should be determined from specimens compacted at the moisture content and dry density as that used in the test sections, where guidance for determination of these values is given in Section E.4. In construction of the test section, the thickness of the base aggregate layer should be adjusted from that in the design condition such that the product of layer coefficient and thickness is identical between the test section and the design.

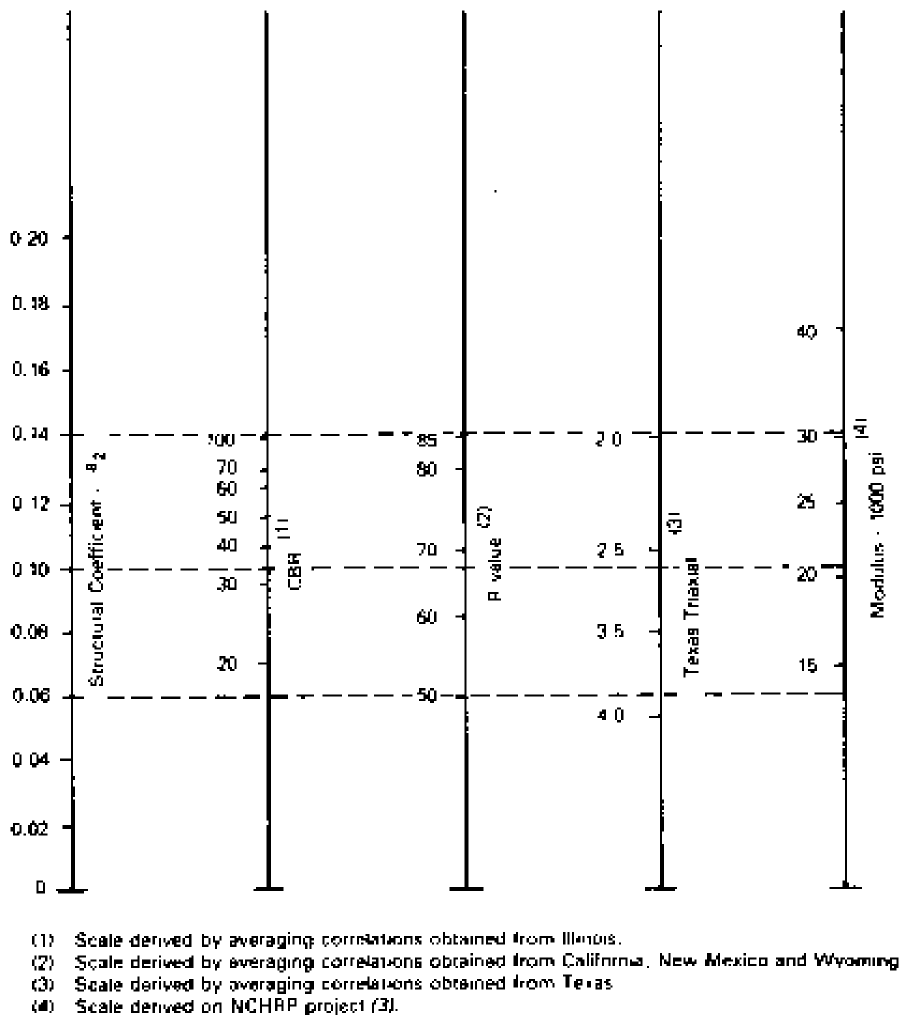


Figure E-5. Correlation between base aggregate structural layer coefficient, a_2, and CBR, R-value, Texas-triaxial, and resilient modulus (AASHTO, 1993).

Similar procedures should be followed for the selection of subbase material, where correlations of structural layer coefficient to CBR, R-value, Texas-triaxial, and resilient modulus are provided in Figure E-6. Similarly, in construction of the test section, the thickness of the subbase aggregate layer should be adjusted from that in the design condition such that the product of layer coefficient and thickness is identical between the test section and the design.

Subgrade material should be chosen to match the classification of that anticipated for the design situation. Unsoaked laboratory CBR tests should be carried out to establish the moisture content and dry density necessary for test section material to match the design CBR assumed. If a CBR was not used in design, appropriate correlations should be used to relate the design parameter to CBR. If resilient modulus was used in the design, the correlation $CBR=M_r/1500$, where M_r is in units of psi, should be used.

The geosynthetic used should be identical to the product being considered for design. Sampling and testing of the geosynthetic should follow the procedures outlined in Section E.6.

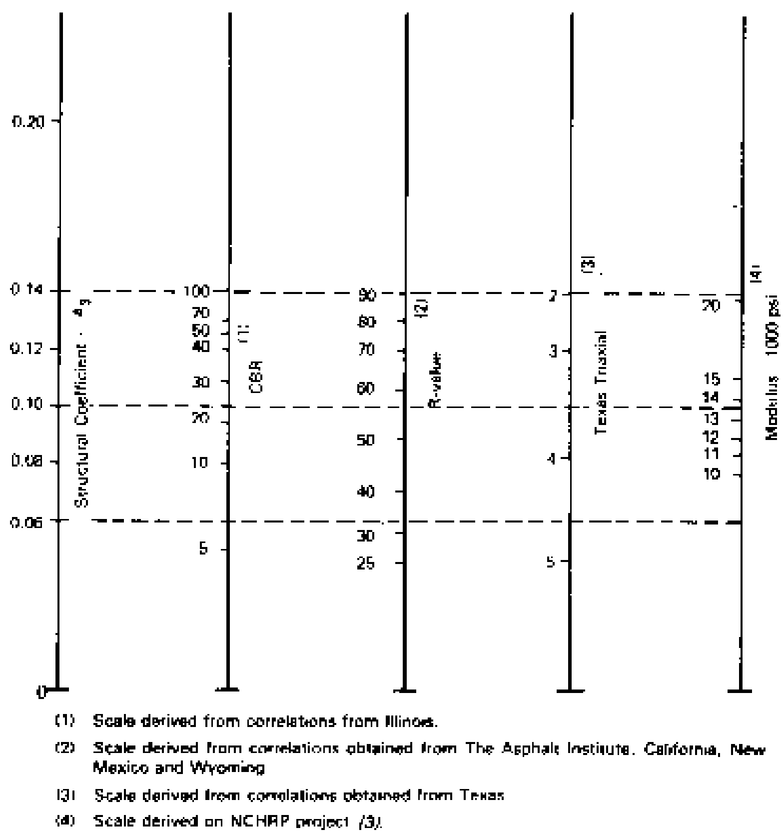


Figure E-6. Correlation between subbase aggregate structural layer coefficient, a_3, and CBR, R-value, Texas-triaxial, and resilient modulus (AASHTO, 1993).

E.4 PLACEMENT AND COMPACTION OF TEST SECTION MATERIALS

In general, test section materials should be placed and compacted to produce materials that match the parameters identified in Section E.3. Construction and compaction equipment should be selected and operated to achieve this objective while also producing test sections of uniform material properties. Quality control measures during the construction process are necessary to document the degree of uniformity of the test sections and are described in Section E.5.

Subgrade material should be thoroughly mixed to the moisture content established in Section E.3, which was based on the moisture content of laboratory unsoaked CBR tests yielding the design CBR. Any subgrade material stockpiled for subsequent placement in the test section should be adequately covered to prevent changes in moisture content. Subgrade can be placed by a variety of methods that produce an in-place dry density and moisture content yielding the design CBR identified by the laboratory unsoaked CBR tests discussed in Section E.3. Exposure of the compacted subgrade should be avoided by adequately covering the placed material once compaction is completed and prior to placement of subsequent material. The thickness of compacted lifts should be dictated by the type of compaction equipment used and should be no greater than that needed to produce uniform compaction throughout the lift.

Modified Proctor compaction tests should be performed on the base and subbase aggregate test section materials. These materials should be placed in the test section at optimum moisture content ± 1% and at 95% ± 2% of maximum dry density. Suitable means of compaction should be used to attain these requirements. The thickness of compacted lifts should be dictated by the type of compaction equipment used and should be no greater than that needed to produce uniform compaction throughout the lift. A minimum initial lift thickness should be used to prevent damage to the geosynthetic during compaction.

Asphalt concrete materials should be placed hot. Sufficient material should be brought to the test site to ensure that the material remains hot up to placement and compaction. Compaction can be undertaken using a variety of methods producing material parameters identified in Section E.3. The thickness of compacted lifts should be dictated by the type of compaction equipment used and should be no greater than that needed to produce uniform compaction throughout the lift.

Geosynthetic material(s) should be placed at the level within, or beneath, the base or subbase as specified in the design being addressed. The geosynthetic should be rolled flat and smooth prior to the placement of aggregate material on top. The material may be pinned at its edges to ensure that the material remains flat and free of wrinkles during aggregate placement. Geosynthetics placed in test-tracks should be placed as they would be in the design situation with respect to direction of placement, overlap of rolls, etc.

Compaction operations should be performed to avoid disturbance of material previously placed. Mixing of the base or subbase and subgrade materials should be avoided. Excessive rutting of the test section during construction should be avoided.

E.5 QUALITY CONTROL DURING TEST SECTION CONSTRUCTION

Test section material sampling and testing during construction is essential to establish the uniformity and quality of the constructed test section and to ensure that valid comparisons between reinforced and unreinforced test sections can be made. The frequency of sampling and testing depends on the size and quantity of materials used in the test section.

Measurements of in-place dry density and moisture content should be made and recorded on each lift of the placed subgrade material. Measurements can be made by nuclear testing devices or by the sand-cone method. Oven-dried moisture contents should be taken to verify nuclear density meter values. Measurements should be uniformly spaced throughout the test section. A measurement of dry density and moisture content should be made for every 0.1 m^3 of compacted material placed. For the test-box shown in Figure E-1, this would require approximately 4 measurements for each 100 mm thick lift.

Measurements for all lifts within a single test section should be used to compute the mean, standard deviation, and coefficient of variation. The target coefficient of variation of dry density and moisture content for the compacted subgrade within a given test section should be no greater than 3%. The target coefficient of variation of the mean values of dry density and moisture content between test sections being used for comparison should be no greater than 2%. The mean value of dry density and moisture content from a test section should be used to determine in-place CBR through correlation to the laboratory unsoaked CBR tests performed as part of Section E.3 to establish the variation of CBR with dry density and moisture content. The maximum deviation of in-place CBR from the test plan design value should be according to the equation:

$$CBR_{in-place} = CBR_{design} \pm 0.1\ CBR_{design}$$

Measurements of in-place dry density and moisture content should be made on each lift of base or subbase placed following the same recommendations for method and frequency of measurement of the subgrade material. The target coefficient of variation of dry density for the compacted base or subbase within a given test section should be no greater than 3%. The target coefficient of variation of the mean values of dry density between test sections being used for comparison should be no greater than 2%. Thickness of the base layer should be established by appropriate means. A minimum of one measurement for every 0.5 m^2 area should be made. The target coefficient of variation of base thickness within a given test section should be no greater than 1%. The target coefficient of variation of base thickness between test sections being used for comparison should be no greater than 1%.

Measurement of the in-place bulk density of the asphalt concrete should be made by coring samples of asphalt sufficiently far from loaded areas after the test section is complete. Approximately one core for every 1 m^2 of asphalt area should be taken. Asphalt air voids should be computed and reported for each core. The target coefficient of variation of bulk density for the compacted asphalt concrete within a given test section should be no greater than 2%. The target coefficient of variation of the mean values of bulk density between test sections being used for comparison should be no greater than 1%. Thickness of the asphalt concrete layer should be established by appropriate means. A minimum of 1 measurement for every 0.5 m^2 area should be made. The target coefficient of variation of asphalt concrete thickness within a given test section should be no greater than 1%. The target coefficient of variation of asphalt concrete thickness between test sections being used for comparison should be no greater than 1%.

During excavation of the test section following loading, the base or subbase aggregate above the interface with the subgrade should be inspected. A grain size distribution of the aggregate directly beneath the pavement load should be obtained and compared to a grain size distribution of the source material to determine whether any amount of subgrade has intruded into the base.

E.6 GEOSYNTHETIC MATERIALS TESTING

Geosynthetic materials received for inclusion in the test section(s) should be sampled according to ASTM D4354. The tests suggested in Table 7-1 should be performed and reported.

E.7 REPORT OF RESULTS

A report should be prepared that summarizes the following details and results.

I Design Conditions and Assumptions

1. Assumed rut depth defining the end of pavement life.
2. Number of ESAL applications assumed at the end of pavement life.
3. Specification for asphalt concrete used.
4. Structural layer coefficient for asphalt concrete.
5. Thickness of asphalt concrete.
6. Specification for base aggregate used and results of material characterization tests if available.
7. Structural layer coefficient for base aggregate.

8. Thickness of base aggregate.
9. Specification for subbase aggregate used and results of material characterization tests if available.
10. Structural layer coefficient for subbase aggregate.
11. Thickness of subbase aggregate.
12. Classification and classification properties (i.e., grain size distribution, plasticity indices) of subgrade.
13. Subgrade design CBR or resilient modulus.
14. Geosynthetic product(s) selected for use.
15. Placement position of geosynthetic product(s).

II Pavement Test Facility Details and Characteristics

1. Type of facility.
2. Test section dimensions.
3. Type, method and frequency of load application.
4. For applied truck traffic:
   - vehicle axle loads
   - wheel type(s)
   - number of wheels per axle
   - computation of ESAL's for the truck used

III Test Section Material Characteristics

A. Asphalt Concrete

1. Asphalt concrete lift thickness.
2. Mean, standard deviation, and coefficient of variation of either Marshall stability or elastic modulus for asphalt concrete as determined from cores taken from outside the loaded area of the test section after the test is completed.
3. Mean structural layer coefficient of asphalt concrete for the test section as determined from correlation with mean Marshall stability or elastic modulus.
4. Mean, standard deviation, and coefficient of variation of asphalt concrete thickness as determined from cores taken from outside the loaded area of the test section after the test is completed.
5. Coefficient of variation of mean values of asphalt concrete thickness between test sections being used for comparison.
6. Mean, standard deviation, and coefficient of variation of in-place bulk density from all asphalt concrete cores within a test section.
7. Coefficient of variation of mean values of asphalt concrete of in-place bulk density between test sections being used for comparison.

B. Base Aggregate

1. Modified Proctor compaction curve for the test section base aggregate and values of optimum moisture content and maximum dry density.
2. Values of CBR, R-value, Texas-triaxial, and/or resilient modulus tests on base aggregate prepared at optimum moisture content and compacted to 95% of maximum dry density.
3. Structural layer coefficient of test section base aggregate as determined from correlations with CBR, R-value, Texas-triaxial, and/or resilient modulus.
4. Thickness of base aggregate lifts.
5. Mean, standard deviation, and coefficient of variation of base aggregate thickness for a test section.
6. Coefficient of variation of mean values of base aggregate thickness between test sections being used for comparison.
7. Mean, standard deviation, and coefficient of variation of in-place dry density and moisture content from all base aggregate measurements within a test section.
8. Coefficient of variation of mean values of base aggregate in-place dry density and moisture content between test sections being used for comparison.

C. Subbase Aggregate

1. Modified Proctor compaction curve for the test section subbase aggregate and values of optimum moisture content and maximum dry density.
2. Values of CBR, R-value, Texas-triaxial, and/or resilient modulus tests on subbase aggregate prepared at optimum moisture content and compacted to 95% of maximum dry density.
3. Structural layer coefficient of test section subbase aggregate as determined from correlations with CBR, R-value, Texas-triaxial, and/or resilient modulus.
4. Approximate thickness of subbase aggregate lifts.
5. Mean, standard deviation, and coefficient of variation of subbase aggregate thickness for a test section.
6. Coefficient of variation of mean values of subbase aggregate thickness between test sections being used for comparison.
7. Mean, standard deviation, and coefficient of variation of in-place dry density and moisture content from all subbase aggregate measurements within a test section.
8. Coefficient of variation of mean values of subbase aggregate in-place dry density and moisture content between test sections being used for comparison.

D. Subgrade

1. Plot of test section subgrade CBR from unsoaked laboratory CBR tests (ASTM D1883) versus moisture content and dry density.
2. Lift thickness for subgrade.
3. Mean, standard deviation, and coefficient of variation of in-place dry density and moisture content from all subgrade measurements within a test section.
4. Coefficient of variation of mean values of subgrade in-place dry density and moisture content

between test sections being used for comparison.

5. In-place subgrade CBR for each test section by correlation of in-place moisture content and dry density to laboratory curves.

IV Geosynthetic(s) Properties

1. Manufacturer's name for product.
2. Description of geosynthetic product.
3. Results of tests performed as per Table 7-1 of this report.
4. Orientation of geosynthetic(s) in test section.

V Measurement Results

1. Mean temperature and maximum change in temperature during loading of the test section.
2. Comment on mixing of base or subbase aggregate and subgrade.
3. Grain size distribution of aggregate above the subgrade interface and directly below the pavement load, and comparison to grain size distribution of source material.
4. For those situations where load is measured, provide a plot of applied load versus load cycle, and report the mean, standard deviation, and coefficient of variation of the applied load for the load cycles measured.
5. Plot of mean rut depth versus applied ESAL for all test sections being used for comparison.
6. If wheel loads are applied, report the standard deviation and coefficient of variation of mean rut depth for the 4 measurement locations corresponding to the end of the test or for a mean permanent deformation of 25 mm, whichever is first.
7. For test sections involving the computation of TBR, compute and plot TBR versus mean rut depth.

E.8 SUMMARY OF TESTING PROCEDURE

Provided below is a summary of the main steps needed for the construction of test sections and the documentation of benefit.

1. Obtain design condition assumptions.
2. Choose and setup the type of test facility (test-box or test-track) to be used.
3. Obtain geosynthetic materials and conduct material tests.
4. Select an asphalt concrete material source.
5. Assume an asphalt concrete structural layer coefficient for in-place test section material based on prior experience.
6. Compute test section asphalt concrete target thickness.
7. Choose base aggregate material source.
8. Conduct modified Proctor compaction test on base aggregate.
9. Determine grain size distribution of source base aggregate.
10. Determine CBR, R-value, Texas-triaxial, or resilient modulus of base aggregate.
11. Determine base aggregate structural layer coefficient by correlation.
12. Compute test section base aggregate target thickness.
13. Choose subbase aggregate material source.
14. Conduct modified Proctor compaction test on subbase aggregate.
15. Determine grain size distribution of source subbase aggregate.
16. Determine CBR, R-value, Texas-triaxial, or resilient modulus of subbase aggregate.
17. Determine subbase aggregate structural layer coefficient by correlation.
18. Compute test section subbase aggregate target thickness.
19. Choose subgrade material source.
20. Conduct sufficient laboratory unsoaked CBR tests on the subgrade at varying moisture content and dry density to bracket subgrade design CBR.
21. Construct test sections obtaining moisture content, dry density, and thickness measurements of various layers.
22. Apply pavement load and measure permanent deformation at prescribed load cycles.
23. Obtain cores of asphalt concrete.
24. Perform tests to establish Marshall stability or elastic modulus of asphalt concrete cores.
25. Determine asphalt concrete structural layer coefficient by correlation.
26. Check asphalt concrete structural layer coefficient against assumed value.
27. Excavate test section, examine aggregate/subgrade interface, and perform grain size distribution on aggregate directly beneath load path and within 50 mm of the interface.
28. Prepare report.

E.9 SUMMARY OF TESTING TOLERANCES

Provided below is a list of the parameters requiring measurement from the test sections and maximum values of coefficient of variation for each parameter.

1. Maximum difference between assumed and in-place asphalt concrete structural layer coefficient: ±0.02
2. Compaction of base and subbase aggregate: ± 1% of optimum moisture content and ± 2% of 95% maximum dry density
3. Asphalt concrete bulk density within a test section: COV $\leq$ 2 %
4. Asphalt concrete mean bulk density between comparison test sections: COV $\leq$ 1%
5. Base and subbase aggregate thickness within a test section: COV $\leq$ 1%
6. Base and subbase aggregate mean thickness between comparison test sections: COV $\leq$ 1%
7. Base and subbase aggregate dry density within a test section: COV $\leq$ 3%
8. Base and subbase aggregate mean dry density between comparison test sections: COV $\leq$ 2%
9. Subgrade moisture content and dry density within a test section: COV $\leq$ 3%
10. Subgrade mean moisture content and mean dry density between comparison test sections: COV $\leq$ 2%
11. Maximum difference between assumed and in-place subgrade CBR:

$$CBR_{in-place} = CBR_{design} \pm 0.1\ CBR_{design}$$